FWD Calibration Center and Operational Improvements: Final Report

April 2007

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U.S. Department of Transportation
Federal Highway Administration

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FOREWORD

The *FWD Calibration Center and Operational Improvements: Final Report* outlines the updates and improvements to the SHRP FWD calibration procedure. It provides information on how to calibrate FWD according to the new procedure. It explains the basic improvements to the procedure and provides the details for 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, and an outline of the new calibration software, *WinFWDCal.*

Gary L. Henderson
Director, Office of Infrastructure
Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
FHWA-RD-06-XX</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
FWD Calibration Center and Operational Improvements: Final Report</td><td colspan="2">5. Report Date
April 2007</td></tr>
<tr><td colspan="2">6. Performing Organization Code:</td></tr>
<tr><td colspan="2">7. Author(s)
David P. Orr, Lynne H. Irwin, and Daniel Atkins</td><td colspan="2">8. Performing Organization Report No.
CLRP 07-XXX</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Cornell University Local Roads Program
416 Riley-Robb Hall
Ithaca, NY 14853</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
DTFH61-04-C-00041</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Office of Infrastructure Research and Development
Federal Highway Administration
6300 Georgetown Pike
McLean, VA 22101-2296</td><td colspan="2">13. Type of Report and Period Covered
Final Report, September 2004 – December 2006</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
HRDI-13</td></tr>
<tr><td colspan="4">15. Supplementary Notes
Contracting Officer's Technical Representative (COTR): Eric Weaver</td></tr>
<tr><td colspan="4">16. Abstract
The objective of this study was 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 involved upgrading the hardware and software used in calibration to take advantages of improvements in technology. The primary result of FWD calibration procedure is still to obtain "gain factors" used to correct FWD load cell and deflection sensor data to agree with the calibration instrumentation. Changes in the FWD calibration procedure include: replacing the reference LVDT with an accelerometer in deflection sensor calibration, development of a multi-sensor holder 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. This report outlines the updated procedures and provides details on the equipment and methods needed to perform the updated protocol.</td></tr>
<tr><td colspan="2">17. Key Words
Deflection Measurement, Falling Weight Deflectometer, Backcalculation, Calibration</td><td colspan="2">18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
171</td><td>22. Price
N/A</td></tr>
</table>

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

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)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND MEASUREMENTS

Abbreviation	Definition
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CD	Compact Disk
CLRP	Cornell Local Roads Program
COTR	Contracting Officer's Technical Representative
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)	1 one-millionth of a meter or 0.0039 mils
mil	1 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

INTRODUCTION

WHY FWD CALIBRATION IS NECESSARY

In 1982, with a grant from the National Science Foundation, the Cornell University Local Roads Program (Cornell) imported the first Falling Weight Deflectometer (FWD) in the United States, a prototype Dynatest model from Denmark. The manufacturer's specifications indicated that the deflections would be accurate to ±2 percent of measurement, or ±2 microns (±0.08 mils), whichever was larger.

In 1984, an early study on the accuracy of falling weight deflectometer measurements found that the specified accuracy involves two separate sources of error. One being the random error of each deflection reading, which is slightly less than 2 microns and independent of the deflection magnitude; and the other being the systematic, or bias, error of 2 percent (occasionally slightly more on some older FWDs). Figure 1 illustrates the effect of these errors on the measured deflection.

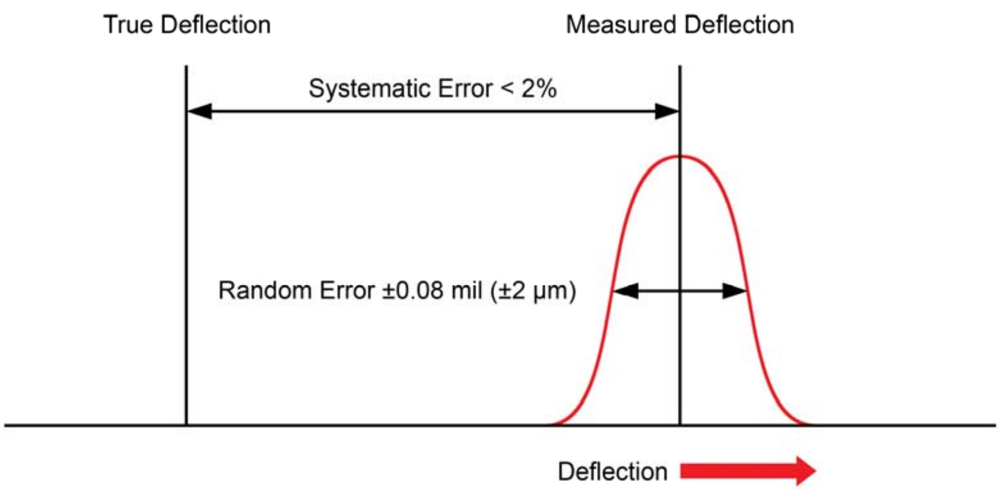

Figure 1. Chart. Random error and systematic (bias) error.

At the first American Society for Testing and Materials (ASTM) Conference on backcalculation in 1988, it was reported that even the 2 micron random error had a very deleterious effect on the backcalculated moduli. Deflection errors of that magnitude could result in layer moduli, particularly that of the surface course, which were incorrect by a factor of two or more.(10)

However, if the systematic error was 2 percent (of reading), then whenever the deflection was 100 microns (4 mils) or more, the systematic error could exceed the random error and produce an even more adverse effect on the accuracy of the backcalculated moduli. These results, combined with the findings of the 1988 conference, emphasized the need to develop a procedure for calibrating FWDs, with the objective of making systematic error as small as possible..

After purchasing four Dynatest FWDs in May of 1988, the Strategic Highway Research Program (SHRP) recognized the need for a calibration protocol that would ensure consistent performance from machine to machine. Later that year, the Cornell Local Roads Program was asked to lead the project to develop a system for calibrating FWDs. The SHRP calibration protocol, written by Lynne Irwin and Cheryl Richter, was finalized in March of 1994 [14], and later adopted by the American Association of State Highway and Transportation Officials (AASHTO).[2]

Four regional FWD calibration centers were established in the fall of 1991 through early 1992. The State Departments of Transportation (DOT) in Pennsylvania, Texas, Minnesota, and Nevada manage them; though recently the Western Center was moved from Nevada to Colorado. Since their inception, the demand for FWD calibration services has risen steadily, and in August of 2001, AASHTO adopted a resolution supporting the continued operation of the four calibration centers.

Due to subsequent changes in technology, however, the original calibration hardware and software was quickly becoming obsolete. Of particular interest was the updating of the *FWDREFCL* software [3] used by the centers, which was originally written as a DOS-based program and utilized a Metrabyte DAS-16G data acquisition board. DOS has since been replaced by the Windows family of operating systems, while the ISA bus required by the Metrabyte board has been phased out of the computer industry.

Similarly, it was recognized that the process of calibration could be streamlined to significantly reduce the time required to perform a calibration. It was also decided that development of a calibration protocol compatible with all makes and models of FWD available in North America was desirable, since the original protocol was designed when only Dynatest and KUAB brand FWDs were available.

PRIMARY TASKS OF STUDY

In 2002, a pooled fund study was proposed to update the existing calibration system. Seventeen State DOTs and the FHWA joined together to develop new methods and equipment to make FWD calibration sustainable for another decade. Overall, the primary goal of the study was to provide *meaningful improvement* to the calibration of FWDs, improvements that exceed the efficacy (speed, accuracy, precision, and repeatability) of the older 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 primary tasks performed during the research are listed below.

Development of a Universal Calibration Protocol

The original SHRP FWD Calibration Protocol works well with Dynatest and has been modified over the years to work with the other brands of FWDs manufactured in the United States. Several specialized sets of hardware were developed to work with each brand of FWD, and the new protocol works with all four brands of FWDs currently sold in the North American market. In addition, the computer software has been written to work with each brand.

Decrease Calibration Time

The motivation for speeding up the calibration process came mainly from the FWD operators. If the calibration procedure takes four hours or less, the FWD operator can be on the road, and in many cases get home without requiring overtime travel or overnight lodging.

By eliminating the manual transfer of data previously required in the reference calibration process, substantial time was saved. In addition, elimination of manual data inputs has reduced the chances of human error. This was achieved by electronic transfer of the data from the FWD computer to the calibration center computer.

Simultaneous reference calibration of the deflection sensors also eliminates a substantial amount of time from the procedure. Previously it took about 20 minutes per sensor to do reference calibration. The sensors were calibrated one at a time, and reference calibration required about three hours for nine geophones. By placing the sensors in a columnar stand and using an accelerometer to measure the actual deflection, up to two hours are saved. The overall time for a calibration should be less than three hours if the FWD is in good working condition.

Replacement of LVDT with an Accelerometer

Replacement of the LVDT with a self-referencing device for use in the deflection sensor calibration was judged to be desirable. This allowed the removal of the block and beam system from the original calibration process. This was done using a Silicon-Designs ±5g accelerometer. Use of the accelerometer is described in the Hardware Updates section on page 20. One major challenge in using an accelerometer was the need to double integrate the acceleration signal to obtain deflections.

Development of Software to Perform All Activities of FWD Calibration

The older SHRP protocol used two different programs to perform FWD calibration: *FWREFCL* and *FWDCal.* In addition, the Calibration Center Operator performed some averaging calculations manually or with a spreadsheet. FWD data were transferred to the calibration center computer manually.

Now, the entire FWD calibration is done with the new software *WinFWDCal*.(5) All files and data are stored with the software as work is completed so that no data are lost if a calibration must stop in the middle of the process. At the end of a successful calibration, the data are transferred to a special folder that allows for historical and forensic analyses of a particular FWD. There is no need for the Calibration Center Operator to perform manual calculations and only a limited amount of data are transferred manually. Figure 2 shows a couple of screen shots from *WinFWDCal.* A general outline of *WinFWDCal* is provided in Appendix IV.

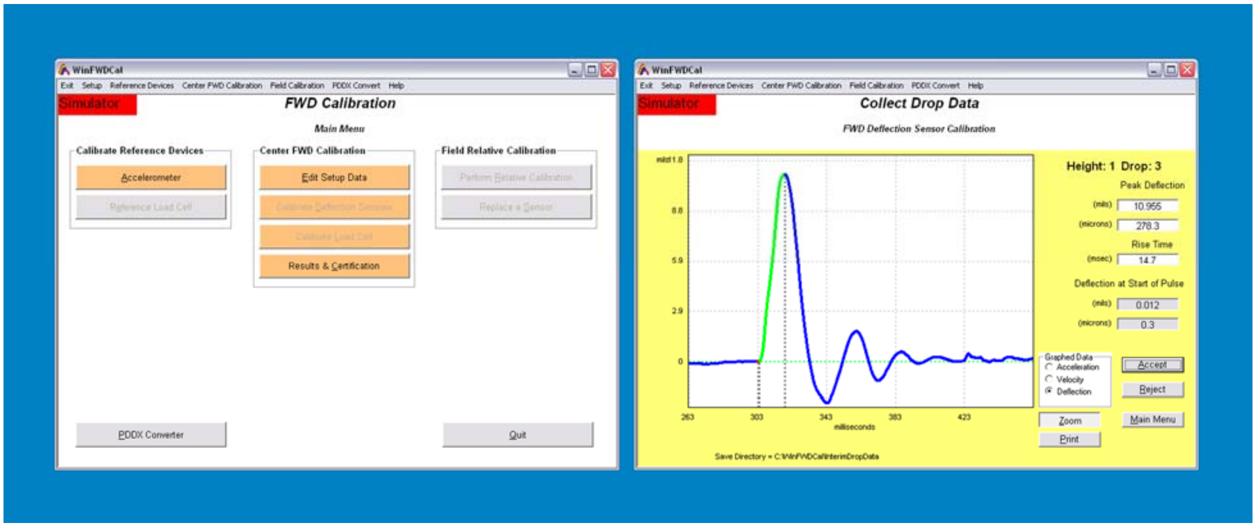

Figure 2. Photo. Screenshots from the *WinFWDCal* software package.

EXISTING SHRP CALIBRATION PROTOCOL

The original, 1994 SHRP calibration protocol was used to obtain “gain factors” which were entered into the FWD’s field software as multipliers. Multiplication of the FWD measurements by the calibrated gain factors resulted in data corrected to agree with the calibration instrumentation. The procedure was developed to work with the known brands of FWDs in the United States in the early 1990s: Dynatest and KUAB. Adaptations were made over time to calibrate equipment from other manufacturers.

The FWD’s deflection and load transducers were first calibrated individually against independently-calibrated reference devices. The deflection sensors were calibrated versus an LVDT using a “block and beam” system. The FWD load cell was calibrated versus a highly precise load cell. This process was called “reference calibration” and was performed at a calibration center.

Results from the reference calibration of the deflection sensors were then further refined by comparing deflection sensors to each other by a process called “relative calibration.” Relative calibration could also be carried out independently at any suitable location to ensure that the deflection sensor were still operational.

There was no relative calibration process for the load cell. The precision of the reference load cell was high enough to meet the need for a balanced measurement system.

The protocol required two people, the FWD operator and the calibration center operator, and the average calibration took about six hours to perform. There were certain times of the year when some FWD calibration centers had to close down due to excessive beam movement.

NEW FWD CALIBRATION PROCEDURE

SYNOPSIS OF THE NEW FWD CALIBRATION PROCEDURE

The new calibration protocol generates gain factors to be used as multipliers on the results from the FWD. As in the old protocol, the new gain factors are entered into the FWD operating system (i.e., the "field program"). The FWD's deflection and load transducers are still calibrated versus independently-calibrated reference devices. In the case of the load cell, there is little difference in the overall calibration procedure.

In the case of the deflection sensors, all of the sensors are calibrated simultaneously by placing them in a columnar stand along with a reference accelerometer. A relative calibration procedure further refines the gains of the deflection sensors and also provides a check of the quality of the calibration. The center-based relative calibration involves a rotation of the sensors to remove any bias due to the calibration stand. All sensors are not in all positions as per the older relative calibration procedure. The older relative calibration procedure can still be used in the field to ensure the proper operation of the deflection sensors.

The new protocol still requires two people, the FWD system operator and the calibration system operator, though it takes less than three hours to perform if the FWD is in good working order and no other problems are encountered. The new FWD Protocol is contained in Appendix I.

WinFWDCal

The new protocol is built into a Visual Basic software program: *WinFWDCal.* The program produces all required outputs, including certification and data from the calibration. No separate calculations are programs are needed to complete an FWD calibration. In addition, it provides a mechanism for the storage of data for historical review.

The program and new procedures can be divided into three different areas: calibration of the reference devices, calibration of the FWD at a calibration center, and field calibration of the deflection sensors. In addition, *WinFWDCal* has a direct link to a FWD data file format conversion program called *PDDX Convert.*

Calibration of the Reference Devices

The calibration of the two reference calibration devices is done versus independent reference systems. This ensures high quality and precision in the FWD calibration.

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 from the Universal testing machine and the output from the reference load cell in volts. The range of the load cell calibration was increased to 24,000 lbs (107 kN) to allow a higher pre-load force from the FWD. A study performed by Orr and Wallace in 2002 confirmed the need for reference load cell calibration on an annual basis.(13)

The reference accelerometer is calibrated on a daily basis with a comparison to the gravity field at the FWD calibration center. By performing the calibration on a daily basis, temperature, hysteresis, and other known variations in the response of the reference accelerometer are reduced to acceptable levels. Non-linear characteristics of the accelerometer are accounted for by a relationship between voltage and acceleration developed by the manufacturer. The daily calibration places the accelerometer in a positive and negative gravity field to provide a slope correction to account for the actual conditions at the site.

Gravitation 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 would result in a difference of about 0.1 percent or less than 0.02 mils (0.5 microns) for a deflection of 20 mils (500 microns).(12)

Center-based Calibration of the FWD

The center-based calibration of the FWD is done in four interlinked 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 center operator. During setup, the FWD is used to determine the number of drops needed for each load level and the trigger level for the reference accelerometer.

Load Cell

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.

Deflection Sensors

The FWD deflection sensors are calibrated in two 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 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 bias in the stands. In the case of KUAB seismometers, there are two columns rather than one. The calibration stand is rotated in the ball joint anchor to eliminate the bias in the stand. As with the load cell, the slope of the regression line driven through zero is used to modify the existing gain of the FWD.

This interim gain is stored internally in *WinFWDCal* and used as part of relative calibration, the second procedure, to provide the final gain factors for the FWD. In relative calibration, forty drops are performed in each of the sensor arrangements used during reference calibration. This eliminates the bias in the stand and provides a large number of drops that are used to improve the precision of the FWD gain values.

Documentation

The final step is to review the data and provide documentation of the calibration. A series of data checks are performed to ensure the results are correct. *WinFWDCal* alerts the user to perform additional tests or repeat the calibration as needed.

During this step, a certificate of calibration is produced along with an electronic data file containing the calibration gains determined during the process. This electronic file is provided 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 FWD calibration results electronic file.

Field Calibration of the FWD Deflection Sensors

Field calibration of the sensors is still necessary to ensure the FWD is operating properly. This involves multiple drops with the sensors in a columnar stand and full rotation of all sensors in all positions. By having all the sensors in all positions, any bias due to the stand and sensors is removed. In addition, if a sensor needs to be replaced then the relative calibration procedure can be used to determine a gain for the new sensor by performing a comparison to the remaining sensors.

PROCEDURAL UPDATES

The new procedure has many improvements and changes, but much of the new procedure uses concepts from the older SHRP protocol. The following section provides insight into the changes in the new procedure. Details on the development of these changes are provided in Chapter 3: Development of the New Protocol.

Overall FWD Calibration Protocol

Despite changes to how reference and relative calibration are done, the overall concept of the two procedures has not changed. A major difference is the user interface, *WinFWDCal.* This Windows based program eliminates the manual calculations necessary in the SHRP protocol.

Data Input

The *PDDX Convert* program allows most of the data from the FWD to be transferred electronically.[4] There is still a need to manually update the gain settings in the FWD under test. This is one of the items that may be improved in the future as FWD manufacturers update their field software.

Reference Load Cell

The reference load cell design remains unchanged from the most recent incarnation. However, the load cell, signal conditioner, signal cable, and data acquisition board are now calibrated as a system to an increased load range of 24,000 lbf (105 kN). All older 5/8 inch (16 mm) thick load cell lids should be replaced with 1 inch (25 mm) thick lids.

Reference Deflection Sensor

An accelerometer replaces the LVDT as the reference device for deflection sensor calibration. This eliminates the need for the concrete block and beam needed in the old protocol. There is still a need for daily calibration of the reference device. This procedure is incorporated into the *WinFWDCal* software.

Data Acquisition System

The Vishay signal conditioner is still used. The major change is the use of a USB data acquisition board (DAQ), rather than the ISA Metrabyte board installed in the computer. From an operational standpoint, the use of the USB DAQ is an improvement since it allows the board to 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 12-bit of the older ISA board.

The triggering concept of trying to detect the release of the mass by the small changes in deflection and load readings has been replaced by *about triggering* of the actual strike of the FWD mass on the load plate. 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.

Drop Sequence

The older drop sequence for reference calibration was fixed at 20 total drops. The number of drops was predicated upon the need to have more than 15.7 mils (400 microns) at the largest load level used in the calibration. Many of the existing FWD calibration centers cannot achieve this deflection level during various times of the year due to seasonal variations in the response of the test slab.

Using impulses from the FWD at the calibration center, the new procedure determines the actual number of drops needed to meet the precision requirements by analysis of the highest and lowest deflection levels when the FWD is in position for calibration. This analysis also allows the number of load levels to be varied as needed for different brands of FWDs. A FWD with a noisy lowest drop level can be calibrated at only three load levels rather than four. In addition, the analysis determines if extra drops are needed when the deflection levels are reduced due to response changes in the test slab. This analysis is contained in *WinFWDCal.*

Data Storage and Partial Calibrations

All of the data are stored electronically, just as in the SHRP procedure. This allows the calibration to be stopped and restarted as needed for a variety of reasons.

Software

The older software packages, *FWDREFCL* and *FWDCal* have been replaced by *WinFWDCal* and *PDDX Convert. WinFWDCal* is used for all steps of FWD calibration. *PDDX Convert* is used to translate native FWD data into the AASHTO PDDX Standard. The major difference in the new software is the user interface. In many screens, the format is almost the same as the older programs. The new programs use more graphics and color to help guide the user. The entire calibration is now done with *WinFWDCal* and there is no longer a need to perform calculations by hand or with a spreadsheet to obtain the final gains.

Deflection Sensor Holder
The use of the multiple deflection sensor stands is a major difference between the new and old procedures. By placing all of the sensors in a column, the deflection sensor calibration can be completed in a fraction of the time needed for the SHRP procedure.

Reference Deflection Sensor Calibration
The calibration of the deflection sensors is still done versus a reference device. The goal of reference calibration is still the same; the resulting gains after reference calibration should be random about truth. In addition, the new center-based relative calibration procedure is used to ensure the quality of the calibration.

Interim Gains
Interim gains are still calculated from reference deflection sensor calibration, but no longer transferred to the FWD computer. The gains are held in the calibration software and used internally with the relative calibration data to determine the new gains.

Relative Deflection Sensor Calibration
The goal of relative calibration is still the same as before; taking enough data to improve the precision of the regression gains around the "truth" determined during reference calibration. The major difference is the elimination of full rotation of the sensors in the calibration stand. Since the stand is very stiff, the sensors only need to be inverted around a common average point to eliminate the variation 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.

Results from FWD Calibration
The final results from FWD calibration are gains for the FWD load cell and deflection sensors. The analyses are now completed by *WinFWDCal.* The program also outputs a calibration certificate.

The results are also provided to the FWD owner in PDDX format. Currently, this is not used to its fullest extent, but it allows the FWD manufacturers to add the ability to read the FWD calibration results electronically with newer versions of their FWD Operating Systems.

FWD CALIBRATION CENTER

Setting Up an FWD Calibration Center

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. The Hardware Use and Installation Guide in Appendix III gives the details about a center, but there are certain basic operational issues that must be discussed prior to ordering equipment and installing a testing pad.

The calibration of an FWD in a center is done to eliminate as many variables as possible while calibrating using the actual wave of the FWD. This requires a test pad 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 in the field.

The preferred size of the slab is 12 feet wide x 15 feet long (4.0 by 4.5 meters), but 12 feet x 12 feet (4.0 by 4.0 meters) is acceptable if space is limited. There should be space around the pad for personnel to move, and to allow maneuvering of the FWD. A larger space is better and at least 5 ft (2.5 meters) is recommended on all sides. The slab needs to be accessible by all brands and models of FWDs and it should be possible to place the FWD and any tow vehicle entirely indoors during calibration to allow FWD calibrations to be performed year round. Table 1 shows an estimated cost for a brand new FWD calibration center.

In addition to the physical constraints 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. Figure 3 shows the full calibration hardware set.

Once a site has been chosen, the testing pad can be installed. A trailer mounted FWD should be driven into the facility, if possible, prior to the installation to help locate the test pad.

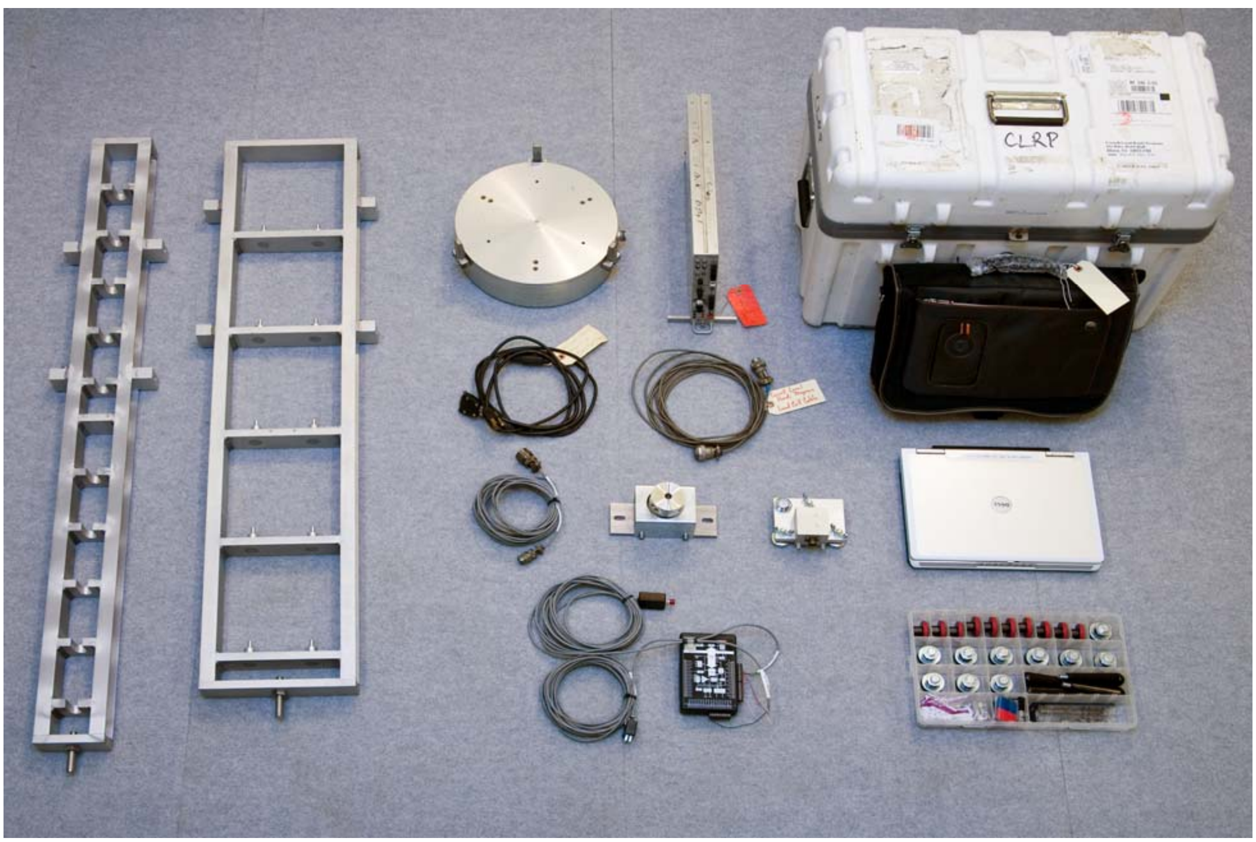

Figure 3. Photo. Calibration system hardware set.

Updating an Existing SHRP Calibration Center

The old beam and concrete block needs to be removed and the new hardware equipment described in Appendix III should be ordered. The existing test pad may still be used. The calibration center computer must be upgraded to meet the requirements. A laptop is recommended. Once the new equipment arrives, the old deflection sensor holder is replaced by the new ball joint anchor.

Training is needed to use the equipment and software. Training should only take a few days, but it is recommended that the FWD center operator performs several trial calibrations prior to the first calibration for a client.

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

Component	Notes	Cost
Accelerometer box	Includes Silicon Designs Model 2220 accelerometer and cables	$1,500.00
Geophone stand	Includes hardware for 10 Carl Bro/Dynatest and 10 JILS geophone adapters	$1,000.00
Seismometer stand	For up to 10 KUAB seismometers	$1,000.00
Floor mount	Includes ball joint and mounting clamp	$900.00
Signal conditioner	Vishay 2310 & 2310-A20	$2,000.00
Data acquisition system	Keithley KUSB-3108 with DAQ cables	$1,200.00
Load cell	Includes strain gauge installation and DAQ cable	$10,500.00
Computer	Laptop model with four USB ports	$1,800.00
		Total: $19,900.00

DEVELOPMENT OF THE NEW PROTOCOL

UNIVERSAL COMPATIBILITY

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 center operators, some FWD owners, and other FWD experts determined what problems are encountered during calibration with the old procedure. The following sections discuss the four brands of FWDs and known problems 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 all four brands of FWD.

Dynatest

The first Dynatest was manufactured in Denmark in 1976, with the first one coming to the United States in 1981.(6) 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 4 shows a model 8000 FWD.

Figure 4. Photo. Dynatest model 8000 FWD

Dynatest FWDs consist of a hydraulically controlled, single mass system. Weights can be removed or added to change the magnitude of the load pulse. The standard equipment places one deflection sensor directly under the load plate and at least six deflection sensors placed along a raise/lower bar. The raise/lower bar runs frontward from the load plate toward the tow vehicle. Optionally, more deflection sensors can be added to the raise/lower bar or to a rear or transverse extension bars. The deflection sensors are velocity transducers, and the deflections are determined using a single integration technique on the response.

During FWD calibration, the model 8081 HWD normal load range exceeds the low load level of 6,000 lbf specified in the original calibration procedure. In order for the HWD to achieve this load requirement, all attached weights must be removed.

JILS

The first JILS FWD was made in 1987 in the United States.[8] JILS manufactures four varieties of FWD listed below.

- **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

Figure 5. Photo. JILS-20T FWD

All of the JILS FWD use a 12 inch (305 mm), rigid steel loading plate, and have optional 12 inch (305 mm) segmented or a 18 inch (457 mm) rigid loading plates. JILS FWD have seven deflection sensors that are placed in a bar that allows the FWD user to position the sensors with optionally two of the sensors on the rear side of the FWD, one on either side, and/or all sensors on the forward side of the loading plate. The deflection sensors are actually velocity transducers, and their response is 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.

Since the standard JILS load plate is slightly larger than the 11.81 inch (300) mm diameter of original design of the reference load cell, the fingers on older reference load cells must be loosened, but not removed, during FWD calibration to allow proper transfer of the FWD to the load cell without damaging the reference load cell. A thicker lid designed for the reference load cell includes a modification to the guide fingers that accommodates the JILS load plate without any modifications to the FWD calibration procedure.

Carl Bro

Carl Bro manufactures both a double-axle trailer mounted and a vehicle mounted FWD.[9] The two loading plate options are a four-segmented 300 mm diameter plate or a full 450 mm 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 loading plate, while the remaining sensors could be placed on the raise/lower bar oriented towards the vehicle or on the side or rear using a T-beam. The deflection sensors are actually velocity transducers, and their response is integrated to determine the deflection**.**

Figure 6. Photo. Carl Bro FWD

KUAB

KUAB has been manufacturing FWD since 1976, with the first one coming to the United States in 1988.[7] KUAB makes both trailer mounted and vehicle mounted FWDs of the single-mass and dual-mass varieties. Most KUAB FWDs use seismometers to measure deflections. Velocity transducers 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 or away from the vehicle. KUAB has the option for either four-part segmented load plates of 11.81 inch (300 mm) or 17.72inch (450 mm) or rigid load plates of 5.91 inch (150 mm), 11.81 inch (300 mm), or 17.72 inch (450 mm).

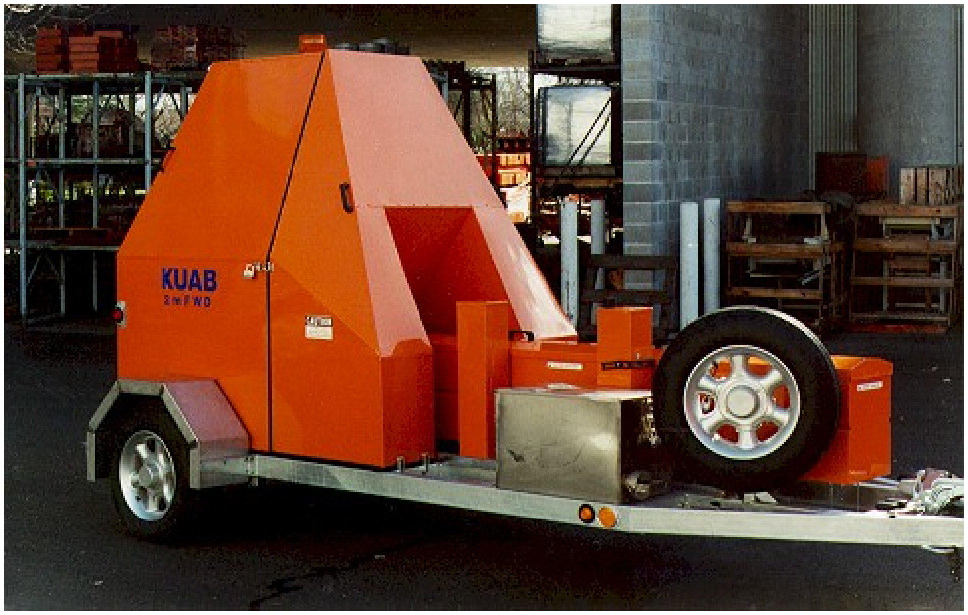

Figure 7. Photo. KUAB FWD with sensors aligned toward the tow vehicle.

For the KUAB FWD with deflection sensors positioned away from the rear of the load plate, orienting the unit close to the beam and block during calibrations can be rather difficult. This can make it difficult to achieve the desired deflections during geophone reference calibration.

Table 2. FWD manufacturers' specifications.

FWD Brand	JILS	Carl Bro	Dynatest	KUAB
Trailer or Truck Mounted	Both	Both	Trailer	Trailer
FWD Typical Maximum Load	20,000 lbs (89 kN)	34,000 lbs (150 kN)	30,000 lbs (130 kN)	16,000 lbs (71 kN)
HWD Typical Maximum Load	50,000 lbs (222 kN)	56,200 lbs (250 kN)	54,000 lbs (240 kN)	135,000 lbs (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 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.

Problems in SHRP FWD Calibration

Based on the results of the interviews and specification reviews, there were numerous problems encountered during FWD calibration. Primary mechanical problems were excessive beam movement and difficulty in getting the loading plate close enough to the beam. Primary electrical problems were 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.

Mechanical Problems

Beam movement was measured using one of the deflection sensors from the FWD under calibration. Figure 8 shows the beam and block combination used in the SHRP protocol. After each set of drops during a deflection sensor calibration, the response from the sensor being calibrated was compared to the sensor being used to monitor beam movement. If there was beam movement greater than 0.12 mils (3 microns) just prior to the start of the load impulse, then the calibration was redone. This wasted time and resulted in the FWD having to come back for another calibration attempt on a later date.

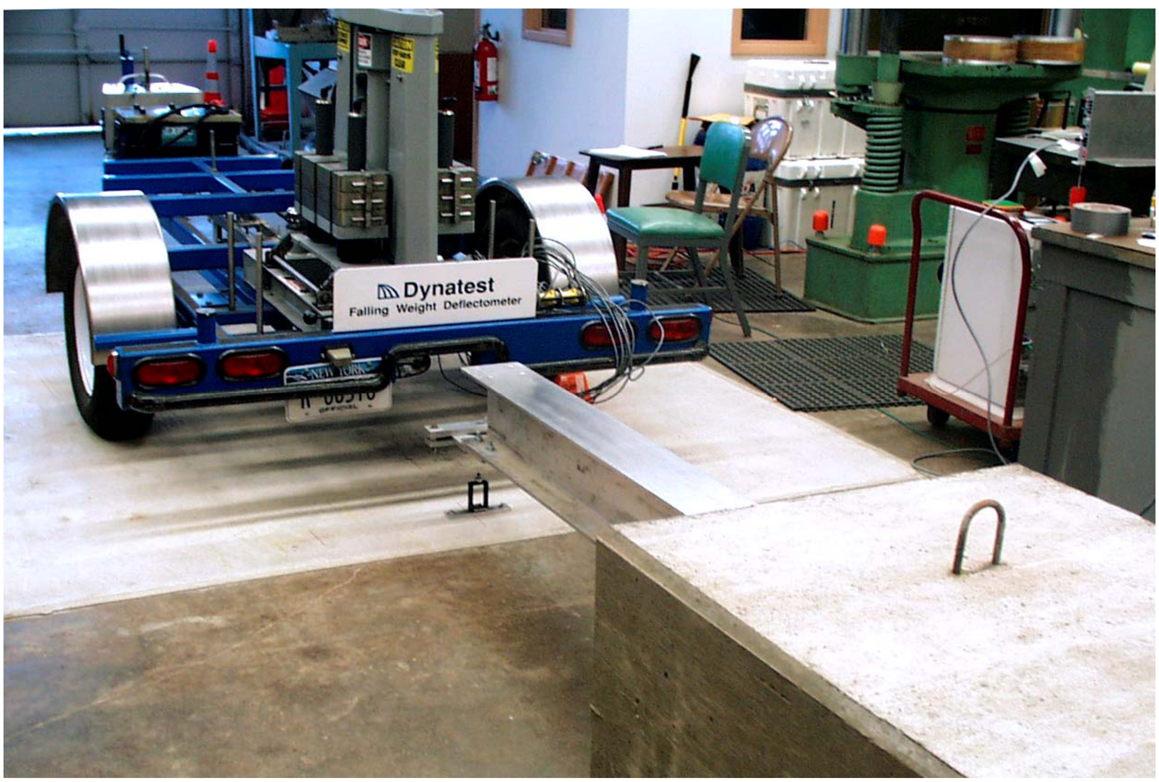

Figure 8. Photo. FWD Calibration Beam and Block.

The SHRP calibration protocol required greater than 16 mils (400 microns) of deflection at the 16,000 lb (71.2 kN) load level during deflection sensor calibration. This means that the loading 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 the KUAB FWD and the Dynatest HWD. Two successful solutions used to allow the load plate to become close enough for the required deflection to be achieved were placing the FWD trailer on blocks so that the rear bumper rises above the end of the beam or bringing the trailer in at an angle to the beam. While these solutions were successful, they inherently added more time to the overall calibration process.

The JILS load plate is slightly larger than the older 300 mm design of the reference load cell. This caused some problems during calibration. When the older reference load cell design was used, the fingers on the sides were loosened in order to accommodate the loading plate and transfer any loads into the measuring links in the reference load cell. With the current newer design for the reference load cell, the guide fingers have been changed to accommodate the JILS loading plate.

Data Acquisition Problems

The most common data acquisition problems were broken into two categories: FWD brand specific problems, and general data problems.

The KUAB FWD has some triggering problems, 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, does not cause a significant vibration at the time of release, and often the data acquisition system failed to initiate data taking as a result.

Data transfer was a considerable problem with the 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 for input into the calibration system. This led to possible transcription errors as well as taking a considerable amount of time. This same problem existed when entering the new gain factors into the FWD computer.

Also, *FWDCal*, a program written to perform the relative calibration tests, only worked with output from a Dynatest FWD. A spreadsheet with macros was written to work with additional data formats, but is not universal.

The lack of a common data file format was also a problem. Currently, each brand of FWD outputs a different data format for entry into the calibration system. This required the center operators to be experts in FWD data output and occasionally required manual calculations to determine the force registered on the FWD load cell from the pressure recorded. Some, but not all, of the different brands of FWD have the ability to directly produce the PDDX data format, which has been suggested for use as a common data format for all FWD.[1] Some FWDs use a separate converter program to change their normal data format into the PDDX format.

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.

HARDWARE UPDATES

Using an Accelerometer in FWD Calibration

After review of many accelerometers in manufacture, the Cornell team found an accelerometer with excellent frequency response and shock resistance. Due to peak accelerations noted during the stand development phase, any accelerometer needs to be able to see a differential acceleration of at least 3g. For this purpose, the Silicon Designs Model 2220-005 ±5g accelerometer (see Figure 9) was chosen. The device offers an optimum combination of low-noise, high sensitivity, and excellent shock resistance.

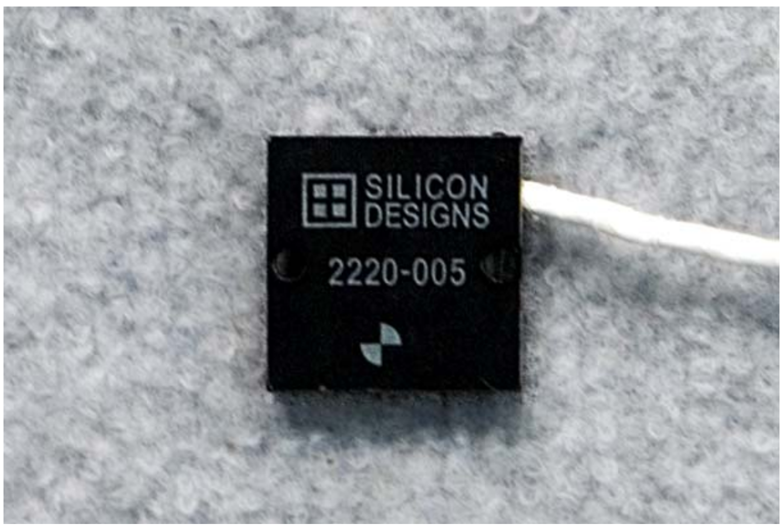

Figure 9. Photo. The Silicon Designs model 2220-005 accelerometer.

The existing Vishay model 2310 signal conditioner is used to power the accelerometer and amplify the response signal by a factor of two, which doubles the device sensitivity. The signal conditioner has a six-pole, low-pass Butterworth filter which is set at 1000 Hz to protect against aliasing.

About Triggering

Modern data acquisition and computer equipment allow the use of a technique called *about triggering* to determine when an event has occurred. Rather than wait for a signal or a threshold value to be reached and taking data from that point forward, about triggering allows the collection of data before and after a signal or threshold value is reached. This means data are taken *about*, or around, a point. This technique is done by storing data in buffers until a trigger is detected and then using the data in the buffers to assemble the complete data set.

In the case of FWD calibration, a full second of data are stored 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.

A*bout triggering* streamlines the data taking process and eliminates the need to have separate hardware to detect the trigger point. It also eliminates the problems of triggering with a KUAB FWD load pulse.

Since the reference load cell measures the load with only a simple calculation to convert the input voltage to load, the trigger for a load pulse is very easy to determine. The load reading needs to be large enough to not be triggered by the application of the preload force when the FWD plate is lowered, but low enough to trigger when the lowest drop level is used. Once the load reading from the reference load cell exceeds the trigger level more than three times in a row, the about trigger point is set. Using three readings ensures no false triggers due to a voltage spike.

In the case of a Dynatest or Carl Bro, the preload is about 1,000 lbs (4.5 kN). For a JILS, the preload can be as high as 3,000 lbs (13.4 kN), while a KUAB preload is very small. Since the collected data encompass a full second, the trigger level for the load can be set very high. As long as the trigger is 2,000 lbs (9.0 kN) less than the lowest load level used in the calibration, the about trigger will work every time for load calibration.

The acceleration trace is very different from the load cell trace and so is the trigger that needs to be used. Originally, the idea was to use a concept similar to the triggering of the load cell by looking for a given acceleration and triggering when it was exceeded. However, a very high frequency, high acceleration, wave pulse occurs upon the release of a JILS FWD mass, causing a premature trigger.

Several different techniques were tested to overcome this difficulty. Ultimately a modified version of an idea provided by Foundation Mechanics, manufacturer of the JILS FWD, was judged the most successful. Not only does a minimum absolute acceleration change need to be detected, but the number of acceleration readings in a row that are above the threshold is used to be sure that the impulse triggering point is in the main wave pulse and not the high frequency mass release. The current number of readings above the threshold value is ten.

The optimum trigger level would be somewhere between the minimum trigger that works at the lowest drop height and the maximum value that actually triggers (as opposed to not even detecting the mass release). Due to the complexities in performing this operation, a subroutine is included in the FWD calibration software to help the FWD center operator perform this operation.

Hysteresis of Silicon Designs Accelerometer

Random errors from the accelerometer pose no problem for calibration. Their significance can be reduced by doing replicate measurements and averaging the results.

Discussions with Silicon Designs uncovered a hysteresis issue with the Model 2220 accelerometer. Every time the accelerometer is inverted in Earth gravity, the bias apparently starts to accumulate again in the opposite direction. The change occurs with time, whether the accelerometer is powered or not and may be 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 measurement errors in excess of 1 percent. The magnitude of the error changes over time while the accelerometer is left at rest in Earth's gravitational acceleration. To overcome this in the FWD calibration, the accelerometer needs to be kept in the +1g field whenever possible and only “flipped” upside-down during the daily calibration. By keeping the time for calibration short, the effect on the overall daily calibration is very small.

Calibration of the Accelerometer

Reference Calibration of the Accelerometer

The Silicon Designs accelerometer is a non-linear device. The output in voltage is not linear with respect to the physical acceleration of the component. In order to overcome this, the manufacturer applies various accelerations and determines a relationship of the form:

$$g = a_3V^3 + a_2V^2 + a_1V + b$$

Figure 10. Equation. Measured acceleration.

Where g = measured acceleration

V = output in volts

a_x, b = coefficients of polynomial

By applying this relationship to the output voltage, the accelerometer can be “linearized.” Due to daily variations in the output of the accelerometer and the increase of the output voltage due to the signal conditioner gain, the voltages from the accelerometer/signal conditioner system need to be adjusted to match the conditions present when the non-linear relationship was developed.

If the accelerometer/signal conditioner system never changed and the gain was exactly 2, then the output voltage could be divided by 2 and the result plugged into Equation 10. Since it is unlikely that the gain is exactly 2 and because of the daily changes in the response of the accelerometer due to temperature and operational issues, the voltage needs to be adjusted by a different amount each time the accelerometer is used.

Since the daily calibration is able to overcome the hysteresis issue mentioned earlier, it meets the needs of the study with very little expense. The accelerometer is calibrated on a flat, level plate that is also used to store the accelerometer and ensure that it is kept in a +1g field (Figure 11).

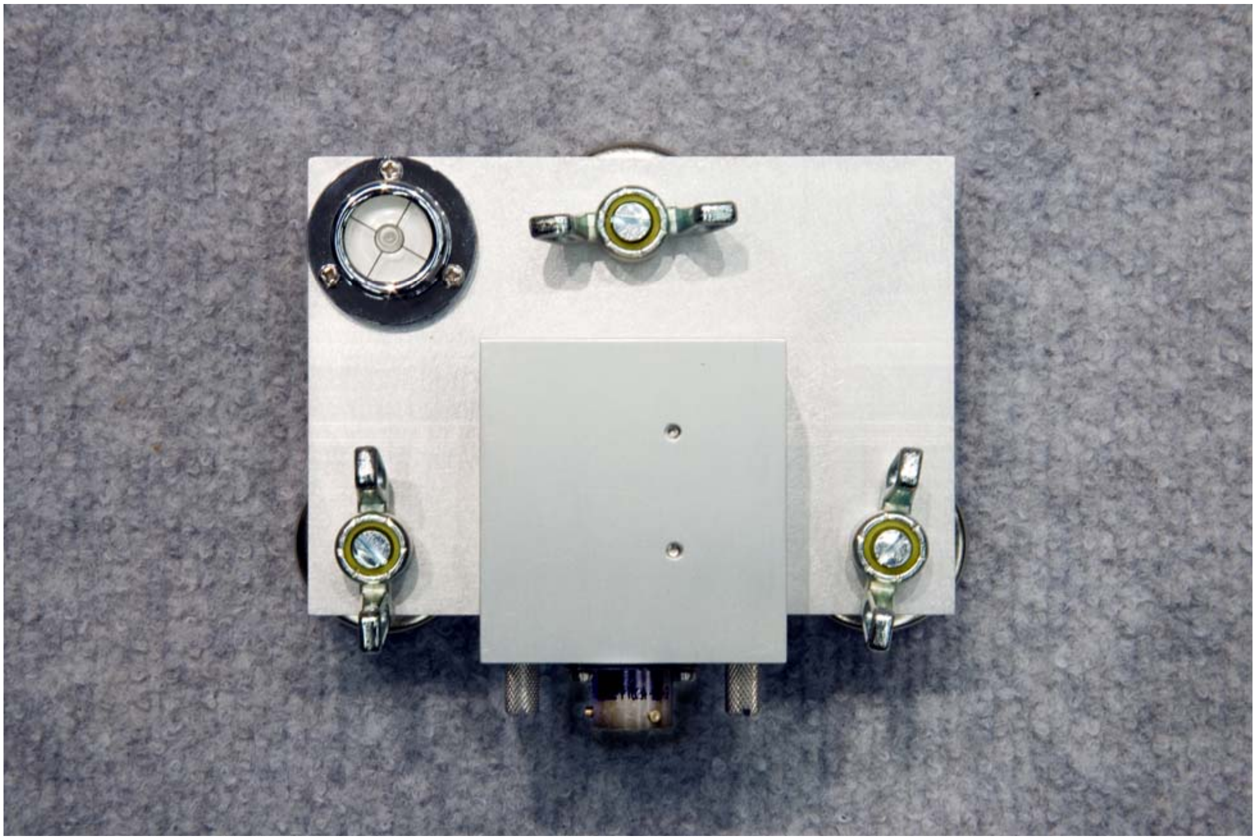

Figure 11. Photo. Accelerometer box on calibration platter.

The daily accelerometer calibration is simple. First, a full second of accelerometer readings are taken in a +1g field. The accelerometer and its protective box are then inverted and another second of readings are taken in a -1g field. Afterwards, the accelerometer is immediately inverted back into a +1g field to keep the hysteresis effect from causing a significant change in the resulting output during FWD calibration.

The averages from the test are used to determine the slope of the voltage-acceleration line. The value of the slope is divided into the output voltage from the accelerometer/signal conditioner system. The resulting value includes the effect of the gain in the signal conditioner and is used with the manufacturer's calibration and linearization relationship to determine the acceleration detected by the device

During the daily calibration, a full second of data are collected and the average used in calculating the voltage versus acceleration slope. The standard deviation of the data is examined to confirm that the accelerometer was stable during the test. The results are also compared to historical data to ensure that the results are typical for the accelerometer under test.

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

Figure 12 and Figure 13 show the effect hysteresis has on the accelerometer. An accelerometer was left in a +1g field overnight. Readings were taken for 15 minutes and were very stable. After those 900 seconds, the accelerometer was inverted into a -1g field, and the voltage output recorded every second (Figure 12). After 30 minutes, the accelerometer was returned back into a +1g field and additional measurements taken (Figure 13). Each figure shows a rapid change in one direction followed by a slower, long-term change in the other direction. Experiments at Cornell showed that if the inversion time (during daily calibration) was kept to under 20 seconds, the effect on the accelerometer voltage would be less than 0.035 percent.

As mentioned earlier, hysteresis occurs in the accelerometer over time, while it is in a fixed position with respect to Earth gravity, and whether or not the accelerometer is powered. When the accelerometer is inverted, the hysteresis begins again in the opposite direction electrically. The most rapid rate of change (of the output voltage) occurs immediately after inversion. If the accelerometer was stored in a -1g field for a long period, it would take over twenty four hours for the accelerometer to equilibrate in a +1g field to within 0.1 percent of the expected long-term voltage output. For these reasons, the accelerometer should be stored in a +1g field.

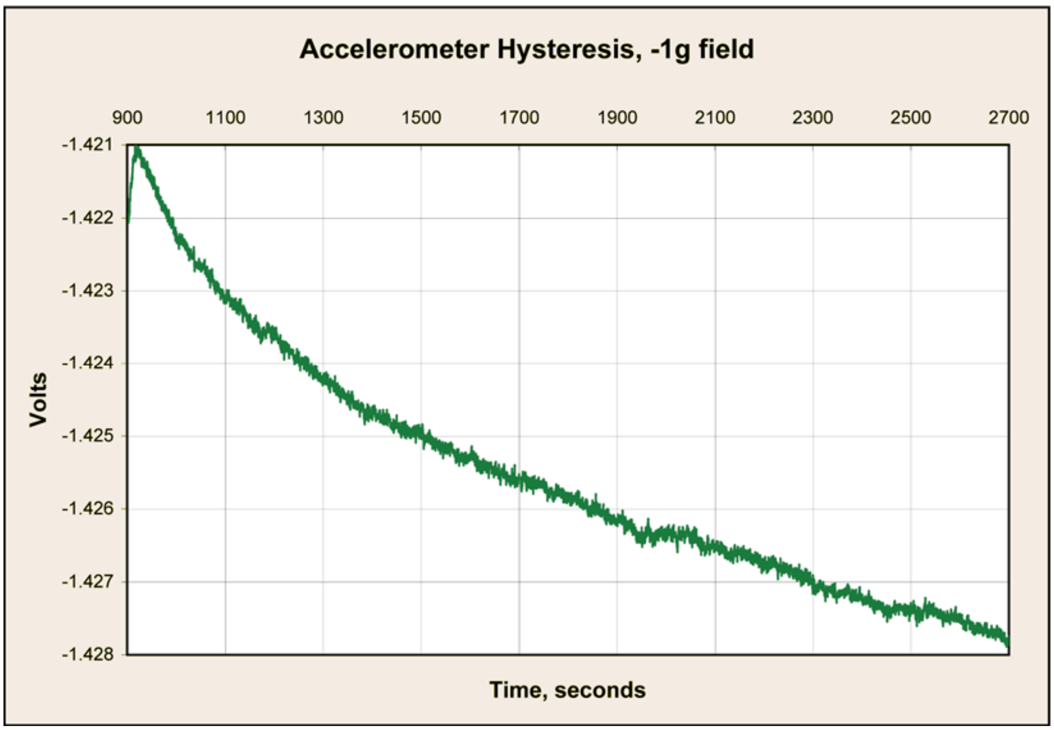

Figure 12. Graph. Hysteresis effect on the accelerometer in a -1g field.

Daily Calibration Data Checks:

Several data checks are completed during the daily calibration of the accelerometer. Some are done to ensure the device is working within normal parameters and others are used to look for changes from calibration to calibration.

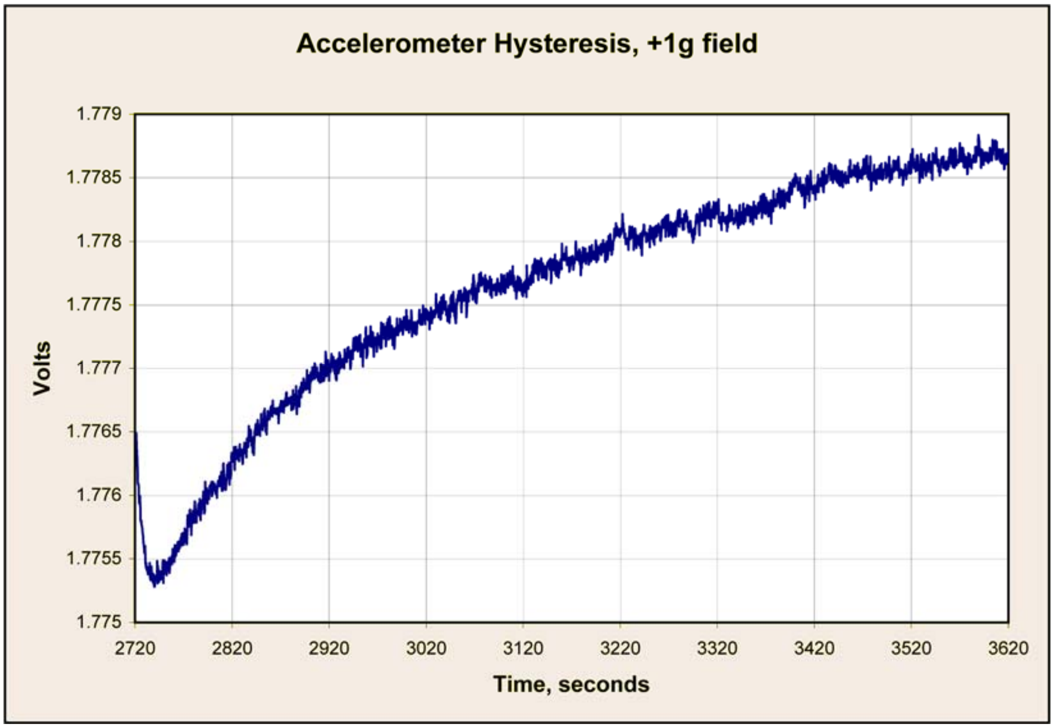

Figure 13. Graph. Hysteresis effect in a +1g field.

- **Temperature change**
  The KUSB board has a temperature measurement on-board that is available as an output from one of the other channels. This temperature is used to ensure that the temperature during FWD calibration is similar to that of the accelerometer calibration. A temperature change of more than 18°F (10°C) is too large. If a temperature change of this magnitude occurs any time during the FWD calibration, the calibration of the accelerometer will need to be repeated. During the calibration itself, the temperature change will typically be very consistent. It is, however, worth noting that the maximum allowable change during the daily accelerometer calibration is 0.9°F (0.5°C).

- **Change in slope**
  The slope of the voltage versus acceleration line should be relatively constant over time even with temperature changes. Currently, no absolute change has yet been proposed for the change of slope from one calibration to the next. Based upon a study of multiple calibrations at Cornell, a maximum change of 0.25 percent should be attainable. A 1.0 percent change is being used as the maximum allowable change until a year or more of FWD calibrations have been completed and the actual field change is determined.

- **Change in offset**
  There is not yet an absolute standard for the change in the zero offset of the accelerometer. The proposed maximum change from one calibration to the next is 0.02 percent, with 0.01 being considered preferable.

- **Overall temperature**
  A temperature sensitivity study examined the behavior of the accelerometer over a range of temperatures well within the expected condition of field calibration and the allowable range of the device. This range (5 to 131°F, -15 to +55 °C) is used ensure that the system is being used in the temperature regime used during development.

- **Time differential during data collection**
  To reduce the effect of hysteresis, the maximum allowable time difference between the data taken in the +1g and -1g fields is 20 seconds. In most cases, the time will be 6 to 8 seconds.

Double Integration of Accelerometer Signal

Use of an accelerometer as a reference in deflection measurement requires a double integration of the output from the accelerometer. Before performing the integration calculations, several boundary conditions and assumptions must be made. Figure 14 shows the acceleration trace from a Dynatest FWD impulse using the Silicon Designs accelerometer.

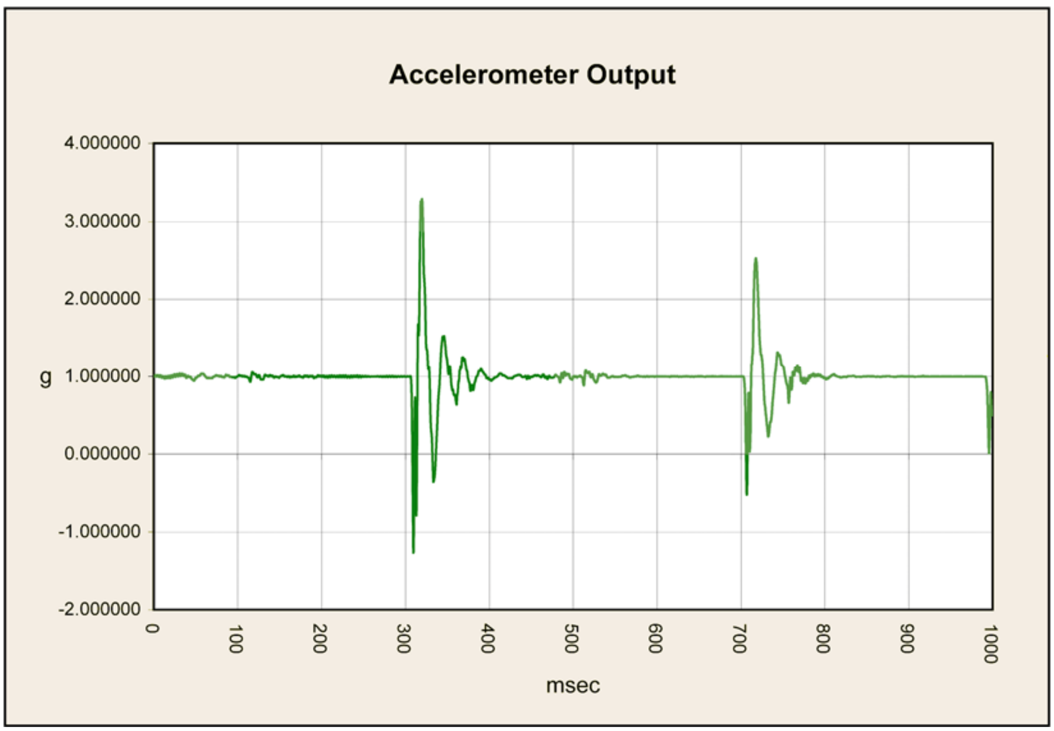

Figure 14. Graph. Raw accelerometer output from Dynatest FWD load impulse.

To double integrate the signal, the acceleration due to Earth's gravity must be removed from the acceleration trace. Otherwise, the resulting integration will include the displacement due to gravitational effects and the calculated deflection will be erroneous. There is the possibility that the testing slab is moving just as the mass package strikes the load plate of the FWD. In this case, the velocity of the slab can also lead to an erroneous result if not corrected for in the calculations. In order to remove the effects of a moving slab and possible acceleration vibrations due to the mass release, a point just prior to the striking of the mass is designated as an initial constraint where the relative accelerations, velocities, and displacements are defined as zero.

Background:
Since the accelerometer starts in a +1g field, double integration of the signal to get displacement requires subtracting out the initial acceleration. This allows the use of differential accelerations in the double integration calculations. Based upon studies of the data at Cornell, even a small error in this offset determination will cause unacceptably large errors in the integration.

The goal of these offset calculations is to determine the initial acceleration and velocity at a known boundary condition that produce the smallest error in the deflection calculations. These biases are subtracted from the accelerometer reading and velocity integration to provide the relative displacement of the device under test. There is evidence that the biases are not constant, but the same studies showed that the selection of the proper bias will produce a random error with a magnitude of less than 1 micron over the short time span of an FWD impulse.

Boundary locations need to be determined. The first is just before the mass strikes the plate. At this time, the displacement is set to zero by the FWD. Even if there is some motion due to other factors, this is a starting point that works for all brands of FWDs. In addition, the relative velocity is set to zero at this time for FWDs using geophones (velocity transducers). The relative acceleration is defined to be zero at this point.

If there is an error in the relative acceleration offset, this error will cause a constant to appear in the integration of the acceleration signal (velocity). This constant error will appear as a parabolic curve in the second integration (displacement). Likewise, failure to account for possible velocity in the slab just prior to the strike point may create an error of integration appearing in the second integration.

By assuming the boundary conditions where the relative acceleration, velocity and displacement are set to zero at the point in time just before the FWD mass strikes its plate, the theoretical error terms will be reduced to the following equations.

$$velocity\_error = ct$$

Figure 15. Equation. Velocity error.

$$displacement\_error = \tfrac{1}{2}ct^2 + k$$

Figure 16. Equation. Displacement error.

c = 1st constant error of integration

t = time

k= 2nd constant of integration

The goal is to then determine *c* and *k* and subtract them from the acceleration trace and the velocity integration. By examining the boundary conditions when acceleration and velocity are expected to be small, *c* can be determined using the area under the *velocity error* curve.

$$Area_{velocity\_error} = \int_{t1}^{t2} ct + k = kt\Big|_{t1}^{t2}$$

Figure 17. Equation. Area under curve due to integration of acceleration and velocity error.

The area of the integration error curve should be approximately zero. As a first assumption, assume *k* is small, and solve for *c*:

$$c = 2 * \frac{Area}{t2^2 - t1^2} = 2 * \frac{d_{t2} - d_{t1}}{t2^2 - t1^2}$$

Figure 18. Equation. Estimate of 1^{st} constant error of integration.

d = displacement at time *t*

The area under the velocity curve is the difference in the integral of the velocity curve from one time to another, or the difference in the measured displacement over a given period of time.

If the second order error is significant, it is still relatively easy to solve for a *c* and *k* that minimize the error using statistical methods of least-squares curve fitting. This assumes the displacement is a parabolic curve with a slope and value of zero at the initial boundary condition just prior to the impact of the FWD mass.

For the final technique used in *WinFWDCal,* the equation in Figure 16 is solved using least-squares curve fitting. The resulting coefficients are used to solve for *c* and *k*. The results are subtracted from any existing values for *c* and *k* already used. Figure 19 and Figure 20 show the resulting integration of the accelerometer trace for a Dynatest FWD impulse.

To determine the initial boundary condition, the *about trigger* time is determined from the acceleration data. A full second of voltage data are collected at 15,000 Hz with 5000 readings before and 10,000 readings after the trigger time. The voltage data are then converted into acceleration data and stored.

The data are reviewed to determine if the about trigger time is correct. All of the calculations described below are completed and the results are examined. If the peak deflection is less than 50 microns or more than 2,000 microns, the FWD calibration program alerts the user that the data are not likely to be correct. In *WinFWDCal*, a plot of the deflection trace shown on the screen can be examined in detail to see if the drop must be repeated.

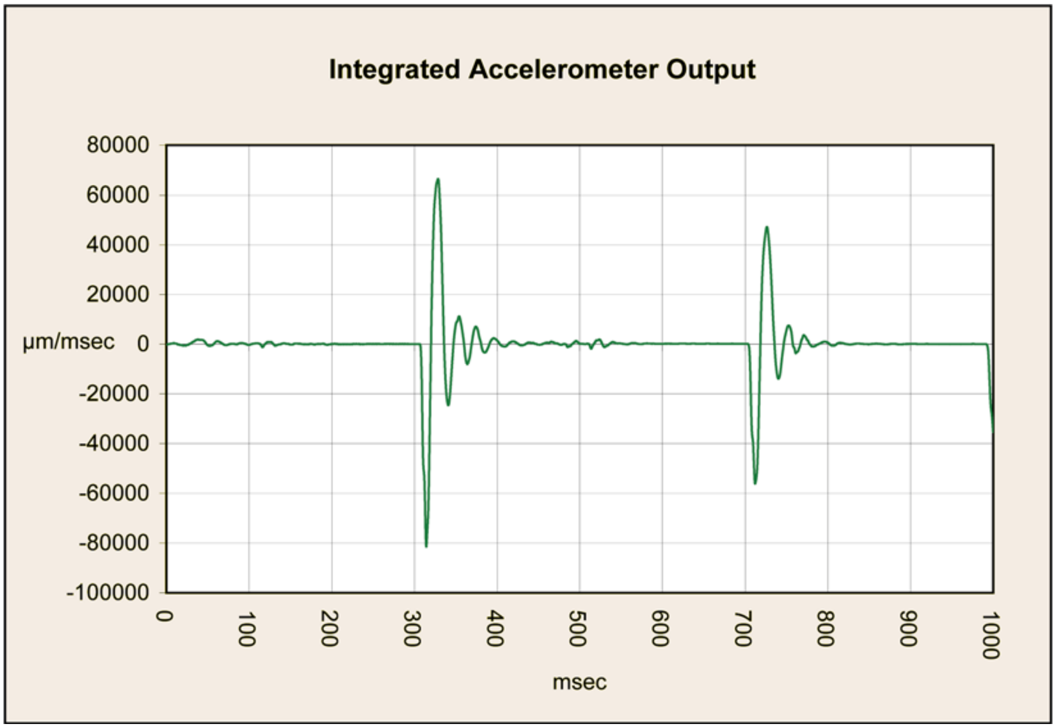

Figure 19. Graph. Accelerometer output after first integration (velocity).

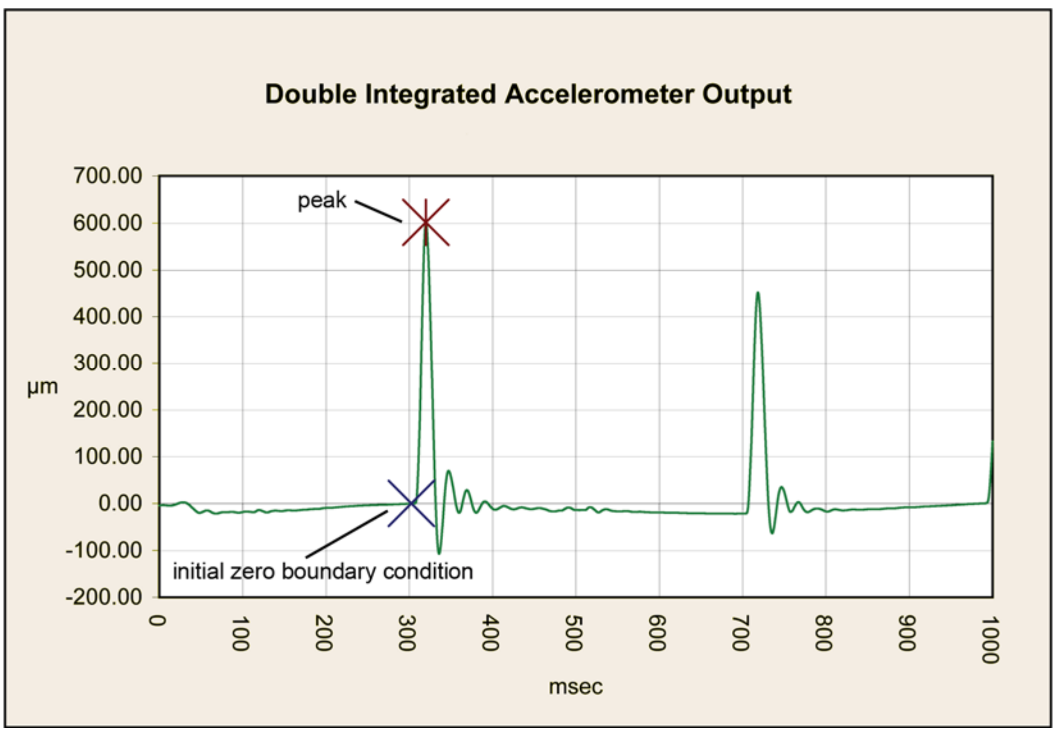

Figure 20. Graph. Double-integrated accelerometer signal (deflection).

Once a trigger point is determined, the algorithm moves backwards from the trigger point 5 msec and takes an average and standard deviation of the data from the previous 5 msec. The standard deviation should be less than 0.02g. If not, the program tries the previous 5 msec since the collected data are too noisy. This can be due to actual noise in the data or inclusion of the beginning of the load pulse in the data. Once a clean data set is found, the end of this 5 msec window is set as the initial zero boundary condition. The relative acceleration, velocity, and displacement are all set to zero.

The initial 5 msec average acceleration is subtracted from all of the data and the resulting relative accelerations are used to determine the velocity and displacement via numerical integration. The displacement data are used in a regression to determine the offset constants. These new values are subtracted from the acceleration and velocity integrations to determine the displacement.

A second iteration is done using only the displacement data that are less than 50 microns in absolute magnitude and is not rapidly changing (based on a velocity of 10 mm/sec). This removes the actual impulse wave peaks and allows a closer examination of the bias in the accelerometer. Internal checks in the FWD calibration software ensure that the second statistical iteration does not actually create erroneous data; which can occur when the initial integration is actually very close to the final result, and the second iteration does not have enough data to properly calculate the errors of integration.

Temperature and Electromagnetic Interference (EMI) Sensitivity:
The feasibility of using accelerometers as reference devices for FWD geophones 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 would fall short of the ±0.3 percent required for deflection sensor calibration.

Silicon Designs reports a temperature shift between -250 and +150 ppm/°C for the model 2220 used in the new protocol. The accelerometer's performance was evaluated at temperatures representative of conditions under which calibration centers in the United States would be running their equipment; which are within the maximum safe operating range of the accelerometer, as specified by Silicon Designs (-55 - 125°C).

Results of the testing at Cornell determined that if the maximum allowable error due to temperature is 0.1 percent, and the maximum acceptable temperature shift is 18°F (10°C). To obtain this result, two accelerometers (serial numbers 277 and 278) were calibrated at various temperatures and the change in the slope due to temperature was determined. Figure 21 shows the change in the slope factor compared to the factor at 25°C versus temperature for both accelerometers. The maximum allowable change in the scale factor was set to 0.1 percent. By dividing the regressed slope into 0.1 percent, the maximum allowable temperature change was determined to be 18°F (10°C).

Electro magnetic 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 the steel box was able to completely defeat the effect of EMF on the accelerometer, its aluminum equivalent showed good results in fields above 1 gauss and was deemed sufficient for use in the calibration protocol. Even large magnetic fields had limited effect on the readings with a maximum change of 0.04 percent change in the voltage output when several high powered magnets were placed next to the accelerometer.

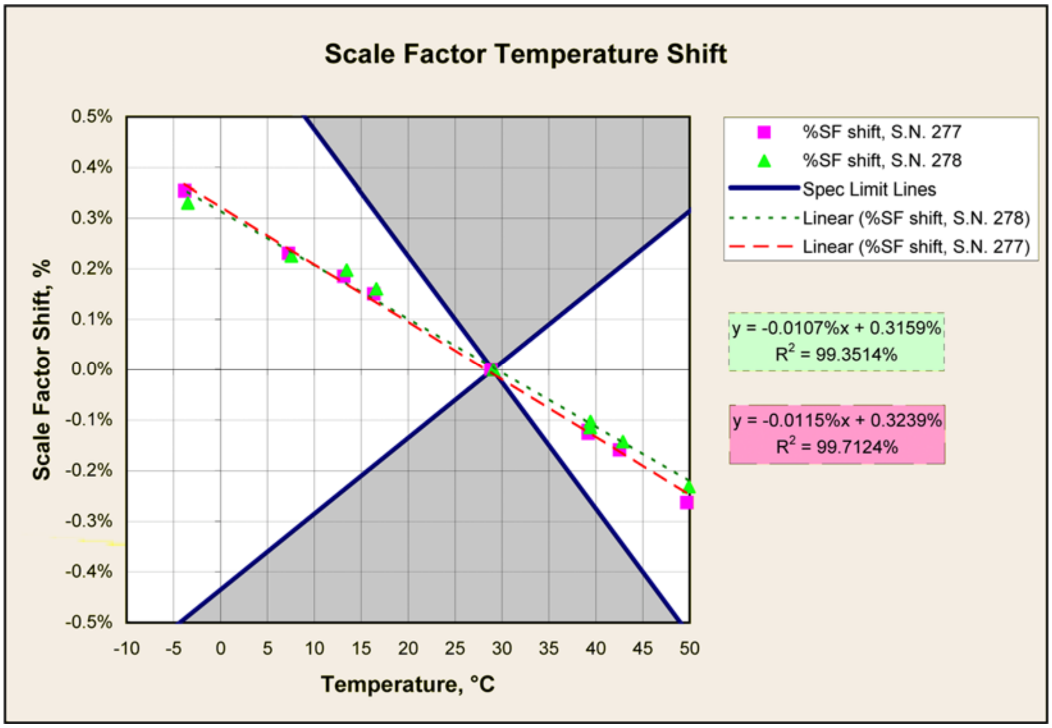

Figure 21. Graph. Scale factor temperature shift for accelerometer.

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 that the aluminum box is not in direct sunlight.

Multi-Sensor Holder

The development of a multi-sensor holder contributed equally to the project's goals of speeding up the calibration process and creating a universally compatible procedure. Time is saved using a multi-sensor holder to eliminate the need to test geophones individually, while the design of the holder made it possible to easily position the stand close enough to the load plates of 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 consistent 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.

Column Design

After examining three different geometries of multi-sensor holders, the vertical column or "ladder" design was found to be the best option for the new calibration protocol. In testing, it was least affected by the rocking and also proved stiff enough to ensure consistent deflections for all positions in the stand.

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 may be simultaneously calibrated using the new stands.

Ball Joint Anchor

Once the columnar design was chosen for the sensor holder, it was discovered that the stand had to be anchored directly to the test-pad. Earlier tests involving an uncoupled anchor, such as is currently used in the field relative calibration stands, showed a person to be incapable of providing enough downward force to keep the stand in contact with the pad and produce consistent results. This problem only is an issue when performing the vertical inversion procedure. Field calibration with full rotation allows the use of an uncoupled tip since all sensors are in all positions and the effects of position in the stand are removed.

Two methods of attaching the calibration stand to the floor were tested. One approach was to bolt the stand directly to the pad with one or two anchors, and the other to connect the stand and pad through a ball joint bolted to the pad.

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. The graph in Figure 22 shows the results of the tests.

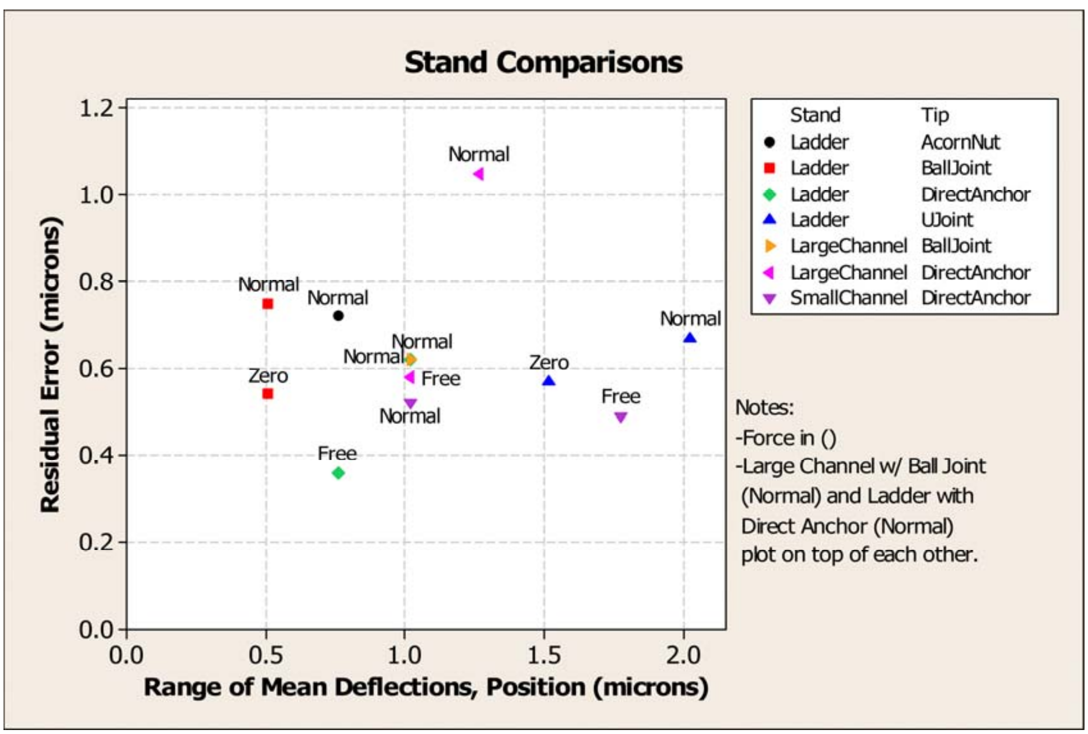

Figure 22. Graph. Comparison of sensor holder stand performance.

Yet despite the efficacy of both, the Cornell team selected the ball joint anchor over the direct anchor for several reasons. It was found that a person holding the stand acts as a dampener and with the direct anchor, it is possible for the stand to be used without being held. The dampening improved the results by reducing the variability of the results. Also, direct anchored stands would be more prone to damage, and less-flexible in terms of maintaining a good, level position.

Reference Load Cell

There were no major changes made to the load cell during the study. Minor changes developed previous to the study to increase the compatibility and useful life of the device are recommended for all load cells. The lid of the load cell should be increased in thickness to 1 inch and the guide fingers adapted to accommodate the slightly larger load plates of JILS FWDs. Once upgraded, the calibration range of the reference cell should be increased to a new maximum load of 24,000 lbs. (106 kN) to accommodate the larger initial static pressure in a JILS FWD.

COMPUTER SYSTEM UPDATES

Software Development

One of the original goals was to update the existing software to a modern, windows-based graphical user interface (GUI) and eliminate the need for manual calculations. While there will always be ongoing updates to any software as complicated as *WinFWDCal*, the original goals were met.

The programming language for *WinFWDCal* is Visual Basic. It was chosen first because the older *FWDREFCL* program used the QuickBasic language and Visual Basic would not require a complete rewrite of the code, and secondly because the KUSB data acquisition card already had drivers for Visual Basic.

The update of the program started in June 2005 with the conversion of *FWDREFCL* 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 with a skeleton version of the new program and built a 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 to obtain real world data. Comments by the center 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.

The updated analyses and engineering calculations were first done with spreadsheets, Minitab statistical software, or by hand to confirm the validity of the calculations.[11] The steps were then provided to the software developers and incorporated into the software in late summer 2006.

During the development of *WinFWDCal* the need arose for a program that converted data from each of the native FWD formats into the one used by the software. The AASHTO PDDX output standard was chosen after discussions with the FWD manufacturers, calibration center operators, and other FWD users.[(1)] This led to development of a self-standing program, *PDDX Convert*. *WinFWDCal* calls *PDDX Convert* internally when converting native file formats.

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 installation at the four regional calibration centers, additional upgrades were made to the program to meet the needs and suggestions of those present.

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 the calibrations performed there. All of this data were combined into a database of historical results, and reviewed to see if there was any need to change the suggestion of annual calibration. The results showed small changes still occur and annual calibration is needed to ensure the proper calibration of FWDs.

Also, the data are to be used for analyzing existing sensors and load cells. The study by Orr and Wallace showed some deflection sensors that have gain settings outside the recommended range of 0.98-1.02.[(13)] However, many of these sensors are stable from one year to the next and the calibration factors correct the measurement errors.

The historical data can be used for sensors with a final gain outside the 0.98-1.02 range to determine if they have traditionally had a gain that is not near 1.0 and, therefore, might not be expected to have a gain within the normal range. By building off the historical database with new calibrations, even new FWDs may be able to use historical trends. This feature is expected to be incorporated into the next major release of *WinFWDCal*.

The data are available and can already be used to evaluate a sensor that fails one of the acceptance criteria. In order to use the database, the historical data are reviewed and an average long-term gain is determined. If the final gain of the calibration is within 1 percent of the long-term average, then the sensor in question would still be acceptable, assuming all other criteria are still met.

Data Transfer

The specialized software package, *PDDX Convert*, was developed to facilitate the electronic transfer of data from the FWD. An electronic file with the FWD data is copied onto a USB flash drive or floppy disk to transfer data from the FWD to the calibration center 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. *PDDX Convert* then adapts the FWD data files to a consistent format, PDDX, that *WinFWDCal* can read and use.

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-outdated 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 in no way backwards compatible with the new standard. An external device, like the KUSB-3108, is easily installed by connecting the device to the calibration center 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, which meant that there was no need for the Cornell team to develop custom drivers of its own.

COMPARISON OF THE OLD AND NEW PROCEDURES

As stated earlier, one goal was to improve performance. However, any improvements had to be made without sacrificing the quality of the calibration. In order to compare the old and new procedures, two sets of data were taken, one using the older SHRP protocol and another using the newly developed system.

Deflection Sensors

Using the Cornell FWD, sensor calibrations were performed with the both the older SHRP and new protocol. Nine calibrations were completed with each protocols. The overall average gain obtained with the new protocol was 0.26 percent higher than the average gain of the older SHRP protocol, which is less than the practical limit of the calibrations due to real world variations in the FWD. Additionally, the variation between calibrations was constant for both protocols.

The dotplot in Figure 23 shows the results from the two protocol tests. The upper half of the graph shows the final gain with the older SHRP protocol. The lower half shows the results with the new protocol.

Load Cell

Twenty load cell calibrations were completed with the SHRP protocol, and 17 with the new. Figure 25 shows the individual value plot of the load cell final gains for the SHRP (old) and new protocols. The overall difference in the average final gain was 0.4 percent. The 95 percentile confidence interval on the difference in the final gain could have been as low as 0.27 percent. The variations for each protocol were the same.

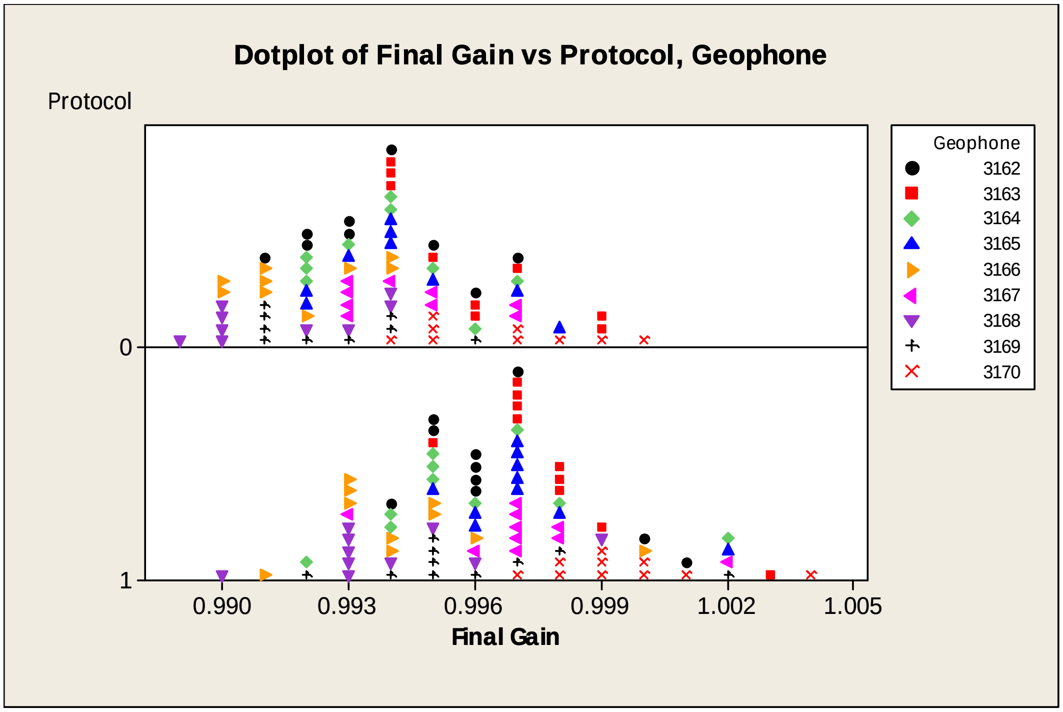

Figure 23. Graph. Comparing deflection sensor final gain values produced with the old (upper panel) and new (lower panel) protocols.

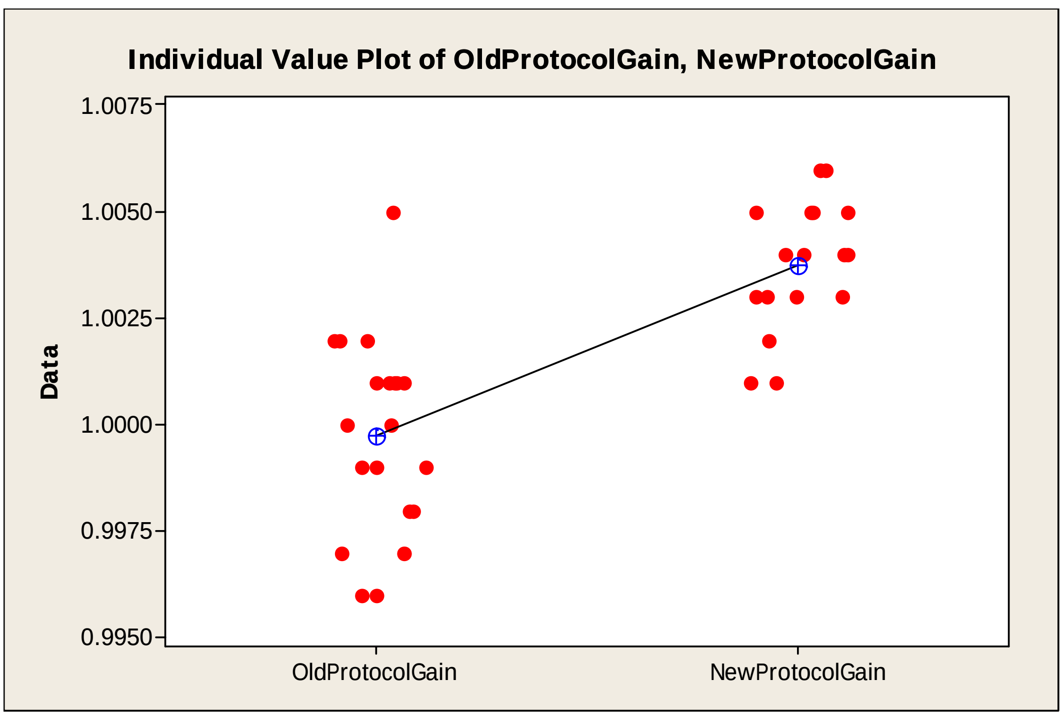

Figure 24. Graph. Individual value plot of load cell final gain values from the old and new protocol.

Comparison of Protocols

While it could be debated that the new protocol is different than the SHRP protocol based upon the results for the load cell and deflection sensors, the practical differences are small. For example, for a deflection of 500 microns (20 mils), the average difference in the two protocols would lead to an error of only 1.3 microns (0.05 mils).

Finally, does the new procedure give the same result as the old one? Statistically, the results would show there is a difference in the average deflection and load, but that each protocol has the same amount of variability. The statistical differences are near or less than 0.3 percent. Differences of 0.3 percent are commonly experienced with calibration of FWDs.

Drop Sequence

The old protocol used a fixed sequence of drops for reference calibration that made use of the program easier. However, in order to obtain the precision necessary, the deflection at the highest load level required a minimum deflection of 16 mils (400 microns). Also, the SHRP protocol required four different load levels with the lowest load level being near 6,000 lbs (26 kN).

Meeting those requirements can be difficult at an FWD calibration center. Both the JILS and KUAB FWDs tend to have noisier data at the 6,000 lbs (26 kN) load level. For both brands, 9,000 lbs (40 kN) is preferred as the lowest load level. The deflection pads at the centers are designed to provide high deflections, but in many cases the peak deflection during certain times of the year are less than 16 mils (400 microns).

In order to overcome these problems, different combinations of drop levels and number of drops at each height can be used to provide the necessary statistical precision. Several constraints were set on the combinations that could be used. As a minimum, three different load levels are needed to verify sensor linearity and provide a range of data in the regression. The load levels should be achievable by the FWD in normal operation and no special weight package should be required. Finally, the number of drops recorded at each load level should be the same to simplify the data analysis.

With these constraints, data taken with the FWD can be used to determine the number of drops needed to meet the precision requirements of the calibration with an assumed error of 0.08 mils (2 microns) for each drop. This concept is automated in *WinFWDCal*.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Overall, the new protocol has greatly increased the speed of FWD calibration without reducing the quality or ease of calibration. The overall the main goals of the study were met.

The new procedure is more universal and 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.

The overall concept of calibration of the load cell and deflection sensors has not changed from the older process. The major changes are the use of the self-referencing accelerometer, the updated data acquisition and computer programs, and the new deflection sensor calibration stands.

RECOMMENDATIONS

- Provide a mechanism to transfer the results of the FWD Calibration into the FWD computer automatically.

  The new protocol eliminated almost all of the manual input of data into the FWD calibration center computer. By reducing the incidence of transcription errors this has increased the speed and accuracy of the calibration. There is no way to completely eliminate the possibility of transcription errors in putting the final gain factors from the calibration into the FWD operating system. Since the values for the gain settings are very close to one another, the chances of reading from the wrong value are higher than desired. This recommendation will require the assistance of the FWD manufacturers.

- Update FWD operating systems to be able to output data in PDDX standard.

  The only place that there is any need for direct typing by the operator in *WinFWDCal* is in the setup of the FWD being calibrated. This is due to the lack of all of the critical data in the output file from the FWD. By producing a complete file using the standardized PDDX data format, this problem can be eliminated. As a minimum, it is recommended that the manufacturers provide all of the pertinent data as part of the FWD output file. This includes all FWD sensor serial numbers, the date of last calibration, and the gain factors for both the load cell and deflection sensors. This recommendation will require the assistance of the FWD manufacturers.

- Update the acceptance criteria of the new protocol after a year or two of use.

  There were many places where the acceptance criteria were not defined as tightly as might be possible. Although additional reviews may be needed, listed below are some of the criteria that should later be examined:

  - All of the acceptance criteria for daily accelerometer calibration
  - Allowable 1 percent change from one calibration to the next with final gain factors
  - A 0.1 percent allowable rate of change for FWD with at least 4 years of calibration history
  - 0.002g noise in the accelerometer signal in the 5 msec preceding the zero boundary condition

- Continue to upgrade *WinFWDCal* and *PDDX Convert*

  With any software package, there will always be a need for updates. Recommendations from the calibration centers and FWD owners needs to be incorporated into the software as soon as is feasible.

APPENDIX I. FWD CALIBRATION PROTOCOL

INTRODUCTION

This document describes the procedure for the calibration of Falling Weight Deflectometers (FWDs), and it updates the original protocol developed by the Strategic Highway Research Program [(1)]. The procedure presented here uses an accelerometer instead of an LVDT as the reference deflection sensor. In addition, new software and hardware are used for the calibration procedure.

This procedure is written for use with the four brands of FWDs currently manufactured or sold in the United States of America. It is *not* applicable to the calibration of cyclic loading or lightweight pavement testing equipment. Due to differences in design of the four brands of FWDs, there are some special procedures for certain brands of FWDs described in the appendices.

In this procedure, the deflection and load transducers from the FWD are first calibrated against independently-calibrated reference devices. This is called *reference calibration*, and it is performed at an FWD Calibration Center. The calibration of the FWD deflection sensors is further refined by comparing them to each other in a process referred to as *relative calibration*. Relative calibration is done as a final step accompanying reference calibration when calibrating at a Calibration Center. Relative calibration can also be carried out as a field procedure, at any suitable location, for periodic verification of the accuracy of the deflection sensors. However, the Calibration Center procedure and the field procedure are slightly different.

The 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

Load cell and deflection sensor calibration at an FWD Calibration Center should be performed at least once per year, or as soon as possible after a sensor has been replaced on the FWD.

Additionally, relative calibration according to the field procedure is recommended to be performed on the deflection sensors at least once per month, and immediately after a deflection sensor is replaced.

Personnel

The protocol requires two people to perform the FWD calibration. 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.

The other person is the *Calibration Center Operator* (or *Center Operator*). This person maintains the FWD Calibration Center and makes sure the calibration equipment is maintained and calibrated as needed. During the calibration, this person is responsible for operation of the Center computer and the specialized software used in the calibration of the FWD. In addition, the Center Operator is responsible for providing the necessary documentation of the calibration exercise.

Upon arrival at the Calibration Center the FWD Operator presents a signed checklist documenting the steps taken in preparation for the calibration, indicating certain preferences concerning the way the calibration should be performed (see Appendix A). The FWD Operator is responsible for programming the FWD computer to carry out the requested procedure. The FWD Operator should provide a history of past calibration results for the FWD to the Center Operator.

During the calibration, the moving of sensors and operation of the specialized equipment is a shared responsibility with the Center Operator having primary control over the calibration equipment.

After completion of the procedure the Center Operator provides 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 is responsible for entering the Final Gain Factors in the FWD computer. The FWD Operator will maintain a cumulative history of calibration results in the FWD computer. The Center Operator will 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.*(2) It is intended that the computer program should be used to carry out the procedure. This program is described in more detail in the *WinFWDCal Software User's Guide*(3).

CENTER-BASED CALIBRATION PROCEDURE

In center-based FWD 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. 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.

Equipment Preparation

Falling Weight Deflectometer

The FWD should be in good operating condition prior to performing 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 Appendix A. It should be filled out prior to arrival at the Center. A copy of the completed checklist should be provided to the Center Operator.

The FWD computer should be programmed to follow the procedure as described in this protocol. Specifically, the FWD mass and drop heights/load levels should be set up to produce loads within ±10 percent of the suggested loads shown in Table 3. The FWD 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 should be used.

Other load levels may be substituted for those recommended 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 24,000 lbs. (106 kN). This limitation is required to protect the reference load cell and the concrete test pad used in the calibration procedure.

Table 3. Suggested Dynamic Load Levels*

Brand of FWD	Load Level 1	Load Level 2	Load Level 3	Load Level 4
Carl Bro	6,000 lbs. 27 kN	9,000 lbs 40 kN.	12,000 lbs. 53 kN	16,000 lbs. 72 kN
Dynatest	6,000 lbs. 27 kN	9,000 lbs. 40 kN	12,000 lbs. 53 kN	16,000 lbs. 72 kN
JILS	9,000 lbs. 40 kN	12,000 lbs. 53 kN	15,000 lbs. 67 kN	18,000 lbs. 80 kN
KUAB	6,000 lbs 27 kN.	9,000 lbs. 40 kN	12,000 lbs. 53 kN	16,000 lbs. 72 kN

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

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

FWD-specific information will need to be transferred from the FWD Operating System (e.g., the FWD data acquisition program files) to the Calibration Center computer. The appendices describe the procedure for obtaining this information for each brand of FWD.

FWD Calibration Center Equipment

Table 4 shows the equipment needed to perform a load cell and deflection sensor calibration at a calibration center. Specification and drawings for all components are in the *FWD Calibration Center and Operational Improvements: Final Report*.[4]

The isolated concrete test pad should be in good condition with little or no cracking. The ball joint base should be attached firmly to the concrete test pad with two anchor bolts to hold the stand in direct contact with the concrete. The stand is clamped in the base. Slippage between the stand and the base, or between the base and the concrete, shall not be allowed.

Table 4. FWD Calibration Center Equipment

Equipment	Notes
Reference load cell with signal cable	30,000 lbs. max. capacity, calibrated annually to 24,000 pounds
Reference accelerometer with signal cable	±5g maximum recorded acceleration, calibrated on the day of use.
Vishay 2310 signal conditioner with power cable	Used to amplify the output from the reference device 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 work with Dynatest, JILS, and Carl Bro geophones.
Seismometer calibration stand	Designed to work 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	Used for generating pavement deflections in the desired range.

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

The accelerometer should be calibrated in the Earth's gravity field just prior to calibration to determine the daily response of the accelerometer. This daily calibration should be repeated after four hours or if the temperature in the testing facility changes by more than 18°F (10°C).

Overview of the Procedure

Either load cell calibration or deflection sensor calibration may be done first, at the preference of the Calibration Center Operator. The *WinFWDCal* software must be used for data acquisition and to make the associated quality assurance calculations.

Some data must be entered in the software before beginning the calibration procedure. Table 5 shows the calibration data reporting requirements and the source of the data. Most of the data are read automatically by the FWD calibration center computer or read in via files copied from the FWD Operating System. All of the data can be updated manually using *WinFWDCal*.

Load Cell Reference Calibration

The FWD load cell should be calibrated at least once. A reference calibration consists of at least two trials. A predetermined sequence of three or four load levels shall be used, with replicate drops for each nominal load level. The *WinFWDCal* software will advise the Center Operator on the recommended number of replicate drops that are required for the selected load levels. More than the recommended number of drops may be used, not to exceed ten drops per load level. The same number of drops should be used at each load level.

The FWD data should be transferred electronically to the Calibration Center computer. *WinFWDCal* will compare the FWD output (independent variable) versus the reference load cell (dependent variable) forced through zero for each calibration trial. The slope of the regression line, when multiplied times the Initial Gain Factor, gives the dynamic calibration factor (gain factor) for the load cell. The slope for an individual calibration trial is acceptable if its reported standard error is not more than 0.0020.

Final Gain Factor Acceptance Criteria

After the two trials have been completed the *WinFWDCal* software will display the gain factors and the standard errors. If the two gain factors agree within a range of 0.003, and both standard errors are acceptable (i.e., not more than 0.0020), then the results of the two trials shall be averaged and used as the Final Gain Factor for the load cell. The reference calibration test is completed.

If the results are outside these limits, 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 three results shall be averaged, and the reference calibration test is completed.

If the standard deviation exceeds 0.003, the load cell reference calibration procedure should 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.

Table 5. FWD Calibration Data Reporting Requirements

Data Item	Mode of Entry	Source
Center Information		
Calibration Center Location	Automatic	Center Configuration File
Calibration Center 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. Accel. 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 Defl. 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
Adj. 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 procedure, the Calibration Center Operator will supply the history of previous calibrations, if one is available.

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

Deflection Sensor Calibration

The deflection sensors should be calibrated at least once. A reference calibration consists of two trials, where all of the deflection sensors are calibrated simultaneously in a special stand. The sensor positions in the stand are inverted between the trials. This is followed by two relative calibration trials where the sensors are inverted once more. Spare deflection sensors should not be calibrated unless they have separate, dedicated signal conditioning channels in the FWD microprocessor.

Reference Calibration

The same load levels used for load calibration should also be used for deflection sensor reference calibration and vice versa. The *WinFWDCal* software will advise the Center Operator on the recommended number of replicate drops that are required for the selected load levels. More than the recommended number of drops may be used, not to exceed ten drops per load level. The same number of drops should be used at each load level.

The software may advise that the deflections are either too large or too small to satisfy the precision requirements for the 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 this does not solve the problem, then no further efforts should be made to calibrate the deflection sensors.

Accelerometer Calibration

Before beginning reference calibration, the accelerometer, mounted in a protective 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 is calibrated in both +1g and –1g 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 Center Operator through the accelerometer calibration procedure and calculate the calibration coefficients. The accelerometer calibration is valid for a period of four hours. The Center Operator will be alerted by the software if the accelerometer calibration needs to be repeated.

The accelerometer box should not be inverted to -1g 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 should be stopped. The box should be placed upright in a +1g gravity field for a period at least four 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 should be allowed to equilibrate for at least four 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. The Center Operator will be alerted if the temperature changes by more than 18°F (10°C). Smaller changes will be of no consequence.

Assembling Sensors in the Stand

The deflection sensors are 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 6 on page 52). The sensor stand should be kept vertical (as indicated by the bubble level) so the accelerometer box will be properly aligned with the Earth's gravity field. The sensor stand should be supported by the rest stop between trials.

During all trials the sensor stand shall be held by a person while the drops are made. For the first reference calibration trial the previously determined series of drops are made and recorded. Before the second trial the sensors are inverted according to the diagram, and the same sequence of drops used in the first trial are repeated and recorded. The *WinFWDCal* software will double integrate the accelerometer signal after each drop to obtain a reference peak deflection that can be compared to the reported FWD deflection results.

The FWD data should be transferred electronically to the Calibration Center computer. For each sensor *WinFWDCal* will compare the FWD output (independent variable) versus the reference deflection sensor (dependent variable) forced through zero for each calibration trial. The slope of the regression line for each sensor for each trial, when multiplied times the Initial Gain Factor, gives the Interim Gain Factor. The slope for an individual trial and sensor is acceptable if its reported standard error is not more than 0.0020.

Interim Gain Factor Acceptance Criteria

After the two trials have been completed the *WinFWDCal* software will calculate and display the Interim Gain Factors and the standard errors for each sensor. If the Interim Gain Factors for each sensors for the two trials agree within a range of 0.003, and all standard errors are acceptable (i.e., not more than 0.0020), then the reference calibration test is completed.

If the results are outside these limits, two more reference calibration trials shall be performed. If the standard deviation of the Interim Gain Factors for each sensor for the four acceptable trials is not more than 0.003, then the four results for each sensor shall be averaged, and the reference calibration test is completed.

If the standard deviation exceeds 0.003, the deflection sensor reference calibration procedure should be repeated (two more trials), inverting the sensors before each trial, yielding a third set of calibration factors. The reason why the standard deviation exceeds 0.003 should be investigated and corrected, if possible, before repeating the procedure.

If, for each sensor, the standard deviation of the three calibration sets (six acceptable trials) is not more than 0.003, the average of all six results should be used as the Interim Gain Factors for the deflection sensors, and the reference calibration test is completed. If this criterion cannot be met, no further effort should be made to calibrate the deflection sensors.

Relative Calibration
Reference calibration is followed by relative calibration, using the same sensor stand. The *WinFWDCal* software will adjust the data collected in the relative calibration, using the Interim Calibration Factors internally. So the FWD Operator should NOT enter the interim factors in the FWD Operating System.

Two trials are performed. For each trial, forty drops are applied from the highest drop height used in reference calibration. The sensors are not moved before the first relative calibration trial. Their positions are inverted in the stand before the second trial. *WinFWDCal* calculates and displays an adjustment ratio for each sensor, when multiplied times the Interim Gain Factor, gives a Final Gain Factor for each sensor.

A graph of the results from the two relative calibration trials should be scanned visually to detect outliers (for instance, a loose senor in the stand). *WinFWDCal* also scans the data and averages the two results to give a single set of Final Gain Factors. If the results of either relative calibration trial are not accepted, then both trials should be rejected, and two additional trials should be done. If acceptable results cannot be obtained after six trials, no further effort should be made to calibrate the deflection sensors.

Evaluation and Acceptance of Final Results

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

1. The Final Gain Factors from this calibration should be compared to the corresponding gain factors from the previous calibration (i.e., the Initial Gain Factors). There should 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 the set of Final Gain Factors should be accepted. If this criterion is not satisfied, then evaluate the next criterion.

2. All of the Final Gain Factors should fall within a range of 0.980 to 1.020. If this criterion is satisfied, then the set of Final Gain Factors should be accepted. If this criterion is not satisfied, then evaluate the next criterion.

3. If a historical record of previous calibrations 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 each Final Gain Factor should be no more than 0.1 percent per year. The *WinFWDCal* software will assist with determining the rate of change.

Certificate of Calibration
If the calibration results are acceptable, the Calibration Center Operator will 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 the data transfer.

Report and Retention of Data
The FWD Operator should be provided with an electronic copy and a hard copy of the calibration results. The full 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.
- Printout of the calibration output that contains the Final Gain Factors for placement into the FWD operational software. (An electronic version of the file should also be provided)
- Pre-calibration checklist
- Results from the reference and relative calibration trials
- Any other print outs produced as part of the calibration.

Any data that cannot be transferred to the FWD computer from the Calibration Center Computer electronically should be printed and included in the documentation of the FWD Calibration. See the appendices for specific issues for various brands of FWDs.

Each of the above printouts 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 should be merged with the history file, a database of previous calibration results for the FWD. Both the FWD operator and the Calibration Center 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.

Suggestions for Successful 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. Before doing any calibrations, verify that the FWD computer and the Calibration Center computer are registering the correct date and time. Correct them before proceeding.

2. 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.

3. The signal conditioner and load cell should be connected and warmed up for at least 15 minutes before calibration begins. This will reduce the variability of the data during calibration. If load cell calibration is done first, the parts can be powered up the night before, to satisfy the warm up recommendation. If deflection sensor calibration is done first, the load cell can be warmed up while relative calibration is being done.

4. 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.

5. At the beginning of each programmed series of drops, add two seating drops for which the data are not recorded. This 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.

6. For load cell reference calibration, position the FWD so that the load plate is near the center of the calibration test pad. 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 improved.

7. Position the reference load cell beneath the FWD load plate making sure that the three guides are properly aligned around the plate. Do not 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

8. 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. Slippage 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 ball firmly but still allow the stand to rotate freely.

9. 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.

10. 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.

Note: The signal conditioner excitation and gain must be set carefully to the levels recommended for the accelerometer.

11. Place the deflection sensors in the calibration stand as shown in Table 6. For the two-column KUAB seismometer stand, use the table shown in Appendix D. 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. The goal is to have the sensors centered on the accelerometer, and to invert them uniformly in the second trial. If additional trials are needed they should be done in sets of two, using the positioning shown in the table.

Table 6. Deflection Sensor 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

12. 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.

13. 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.

14. 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 9,000 pounds (40 kN) 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 is of concern before rejecting the calibration.

    - 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 25 lbs (0.11 kN) for the load cell, and 0.16 mils (4 microns) for the deflection sensors, are acceptable regardless of the ratio.

15. When not in use, the load cell, accelerometer and other calibration equipment should be stored in a protected location. The accelerometer should be stored in a +1g 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.

16. 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.

FIELD-BASED RELATIVE CALIBRATION PROCEDURE

Field-based relative calibration can serve two purposes. In monthly 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 calibration of the replacement sensor until a center-based calibration can be done.

Field-based relative 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. Research has shown that 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 what is done in center-based relative calibration.*

Relative calibration relies on collecting a large amount of data that can be averaged to reduce the significance of random measurement errors. Deflections in excess of 20 mils (400 microns) 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 should be modified to simultaneously calibrate the actual number of active sensors in use on the FWD.

Equipment Preparation

Falling Weight Deflectometer

The FWD should be in good operating condition prior to performing relative calibration. A well maintained FWD is easier to calibrate and less prone to mechanical and electrical problems during calibration and during general use.

Before beginning any calibration work, and throughout the entire calibration period, it is necessary that there be no data filters in operation in the FWD. The FWD Operator should verify that any smoothing or filtering has been turned off.

Prior to starting the calibration, the FWD should 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 are 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 are moved through the various positions in the calibration stand in a prescribed way. 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) is "conditioned" before beginning the calibration procedure to reduce the significance of set in the data analysis. The rotation procedure between sets is shown in Table 7 for a nine-sensor system and Table 8 for a seven-sensor system.

Relative Calibration of the Deflection Sensors

1. Condition the test point by repeating a sequence of ten drops until the loads and deflections that are registered are nearly uniform. The deflections should not be showing a steadily increasing trend (liquefaction). If the deflections are steadily increasing, then choose a different location for the test.

Table 7. Relative 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 8. Relative 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

2. 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 would be labeled D1 for this procedure.

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

4. Position the deflection sensors in the stand for the first set as shown in Table 7 or Table 8.

5. Support the sensor stand in a vertical position. Mark the location where it rests so that it can be relocated precisely on the same spot. This could be done by gluing a washer to the pavement, or by chipping a small divot in the pavement with a chisel or a screwdriver.

6. Select the FWD drop height and the distance from the loading plate to the sensor stand to yield deflections near 20mils ±4 mils (500 microns ±100 microns). 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.

7. 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.

8. For each set, make two seating drops (no data recorded) followed by five replicate drops (for which data are recorded) while holding the stand in a vertical position.

9. At the end of each set rotate the sensors in the stand as shown in Table 7 or Table 8. 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.

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

Relative Calibration Data Analysis

Transfer the FWD data file to the *WinFWDCal* software program for analysis. Follow the directions in the *WinFWDCal Software User's Guide*.(3) 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 Final Gain Factors for each deflection sensor. Since sensor replacement is not involved, the adjustment of the gain factors in the FWD Operating System should be made only when those changes are both significant and verified to be necessary. The following guidelines should be used to evaluate the need for adjustment of the gain factors:

- Research has shown that computed sensor adjustment ratios between 0.997 and 1.003 inclusive are not significantly different from a ratio of 1.000. In other words, the required adjustments are trivial and do not need to be made. The calibration test is completed, and no change of the gain factors should be made.

- When the adjustment ratios for one or more sensors fall outside of the range 0.997 to 1.003, a second relative calibration trial shall be performed. If the Average Final Gain (average of the Final Gains for all deflection sensors) in both sets of data agrees within 0.003, the need for the adjustment has been verified and the gains should be adjusted for *all* sensors if the following criterion is satisfied. The full set of Final Gain Factors should be entered in the FWD Operating System.

- If this criterion is not satisfied, a center-based calibration should be performed as soon as possible.

Adjustment of Gain Factors – Sensor Replacement

When replacing a damaged deflection sensor, the field-based relative calibration procedure can be used to determine a gain factor for the replacement sensor. The calculations are done by the *WinFWDCal* software, and a Final 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 results of the two trials shall be averaged and used as the Final Gain Factor for the replacement sensor. The calibration test is completed.

If the results are outside these limits, a third relative calibration trial shall be performed. If the standard deviation of the gain factors for the three trials is not more than 0.003, then the three results shall be averaged and used as the Final Gain Factor for the replacement sensor. The calibration test is completed

The Final Gain Factor should be entered in the FWD Operating System. A center-based calibration should be performed as soon as possible.

If the standard deviation is more than 0.003, no further effort should be made to calibrate the replacement sensor.

Report

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

APPENDIX 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 Serial/ID Number: ____________________

FWD Manufacturer: ____________________

FWD Owner: ____________________

- ☐ 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 your load plate swivel is properly lubricated, if applicable, and that all bolts are tight. Refer to your owner's manual for instructions. Assure that the load plate has a 12 inch (300mm) diameter.
- ☐ 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 for 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 formatted 3-1/2" diskette or a USB thumb drive for transfer of the FWD data to the Calibration Center computer.
- ☐ Store your operating manuals in the FWD vehicle, incase of any unforeseen problems.
- ☐ Check the integrity of all batteries with a hydrometer or load tester. Check battery terminals for corrosion and clean if necessary.
- ☐ Check hydraulic fluid level(s) and assure that they are at the proper fill point. Inspect the hydraulic system for any leaks.
- ☐ Verify that the proper testing setups are programmed into the FWD software for both reference and relative calibration. Name and save the setup files.
- ☐ Select the unit system and three or four target load levels to be used for calibration.

Unit system:	Target load levels:	
☐ US Customary(lbs)	1. ____________	3. ____________
☐ Metric	2. ____________	4. ____________

Adjust or calibrate the FWD to achieve the target levels within ± 10 percent.

- ☐ Turn off any filtering (smoothing) in the FWD Operating System.
- ☐ Have data files and/or hardcopies from the previous calibration(s) available.

Operator's signature: ____________________

APPENDIX B. SPECIAL PROCEDURES FOR TESTING A DYNATEST FWD

- The electrical system of the FWD should be fully charged so that the vehicle engine does not need to be turned on during the calibration. The FWD may be powered by battery chargers as needed to provide power.

- The FWD trailer should remain 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 3.5 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 achieve the required clearance.

- Since the sensors for the Dynatest are magnetic, the reference calibration stand hardware can be assembled prior to the arrival of the FWD. The knurled steel nuts should be placed above the shelves in the calibration stand. The knurled steel nut should be torqued by hand tightening the hardware. Do NOT use a wrench to attach the hardware.

- Clean the bottoms of the geophones and remove any small stones or other debris that interfere with proper contact of the magnetic mounts. An emery cloth does a good job for this activity. The FWD operator should complete this cleaning PRIOR to arrival at the calibration center.

- The FWD Operating System (i.e., the field program) should be programmed to provide the output of the FWD in either F25 or F20 format, with F25 being preferred.

APPENDIX C. SPECIAL PROCEDURES FOR TESTING A JILS FWD

The electrical system of the FWD should be fully charged so that the vehicle engine does not need to be turned on during the calibration. The FWD may be powered by battery chargers as needed to provide power.

The FWD trailer should remain attached to the tow vehicle during the calibration, if applicable. The geophone sensor bar attached to the back of the FWD must be removed as needed to allow the FWD to get close to the ball-joint anchor.

After removing the deflection sensors from the FWD, attach each geophone in the calibration stand. The knurled steel nut should be torqued by hand tightening the hardware. Do NOT use a wrench to attach the hardware.

The JCAL Operating System software may require the FWD Operator to release each drop manually. It may not be possible to program the desired drop sequence. A form can be printed from *WinFWDCal* to help the FWD operator keep track of the drops that have been made.

APPENDIX D. SPECIAL PROCEDURES FOR TESTING A KUAB FWD

- The electrical system of the FWD should be fully charged so that the vehicle engine does not need to be turned on during the calibration. The FWD may be powered by battery chargers as needed to provide power.

- The FWD trailer should remain attached to the tow vehicle during the calibration.

- Before the reference calibration procedure is performed, the FWD Operator should first conduct a static calibration of the deflection sensors, if applicable. The KUAB software will automatically file the static calibration factors.

- 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 in position number 1 as far as *WinFWDCal* is concerned.

- 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. A form can be printed from *WinFWDCal* to help the FWD operator keep track of the drops that have been made.

- In order to provide the pause needed after each drop during reference calibrations, the KUAB Operating System software can be set up to perform manual drops.

- Because the top of the reference load cell is 11.81 inches (300 mm) in diameter, it will only be possible to calibrate the small (11.81 inch (300 mm)) load cell on the KUAB. If the KUAB is outfitted with load cells having a diameter larger or smaller than 11.81 inch (300 mm)s, these should not be calibrated using the 11.81 inch (300 mm) reference load cell as the results would not be accurate.

- A special two-column seismometer stand is used for deflection sensor calibration for KUAB FWDs with seismometers. The sensors mount on standoffs of the same size as the ones on the FWD. After the set screw has been tightened the seismometer should be firmly attached and it should not wobble or rock on the standoff.

- For a seven-sensor FWD, the location of the sensors in the seismometer stand is shown in Table 9. If the number of sensors is different than seven, *WinFWDCal* will show the location of the sensors as needed to be properly centered above and below the accelerometer.

- A special one-column calibration stand is used for KUAB FWDs with geophones. Place the deflection sensors in the calibration stand as shown in Table 6. 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. The goal is to have the sensors centered on the accelerometer, and to invert them uniformly in the second trial.

- Enter the Final Gain Factors for the deflection sensors as the "dynamic calibration factors." At the present time there is no place in the KUAB Operating System software to enter the gain factor for the load cell. Thus load cell testing should be considered to be "calibration verification."

Table 9. Deflection Sensor 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
J (bottom)	D7	Empty	Empty	D7

Note: For Trial 1 the left column, with sensors D1, D3, etc., should be closest to the FWD load plate. For Trial 2, rotate the stand on the ball swivel so the column with sensors D1, D3, etc. is furthest from the FWD load plate.

APPENDIX E. SPECIAL PROCEDURES FOR TESTING A CARL BRO FWD

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

- The FWD trailer should remain attached to the tow vehicle during the calibration, if applicable.

- 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. A form can be printed from *WinFWDCal* to help the FWD operator keep track of the drops that have been made.

- In order to provide the pause needed after each drop during reference calibration the Carl Bro Operating System software can be set up to perform manual drops without raising the plate only after performing any seating drops and at least one recorded drop. The FWD operator should prepare a list of the drops needed ahead of time and be prepared to *reject* the first drop after the seating drops.

- After removing the deflection sensors from the FWD, attach each geophone in the calibration stand. The knurled steel nut should be torqued by hand tightening the hardware. 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.

APPENDIX F. 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, and the associated signal conditioner, and data acquisition board should be considered a system of instruments, which should be calibrated together and used together. The load cell should be calibrated to a maximum load of 24,000 lbs (100 kN)

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

This procedure has been automated and is included in *WinFWDCal.*

Frequency of Calibration

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

Equipment

- Universal testing machine.

  A static testing machine, hydraulic or screw-powered, with a load capacity of 100,000 lbs (500 kN) or more should be used for the reference load cell calibration. Although the reference load cell will only be calibrated to a capacity of 24,000 lbs (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 0-30,000 lbs (0-130 kN) range (slightly different ranges, such as 0-24,000 lbs (0-100 kN), etc., would be acceptable as long as the entire range of the load cell can be calibrated in a single range on 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.
- Measurements Group, Inc. Vishay model 2310 signal conditioner. This should be the same signal conditioner that will be later used in the FWD calibration procedure.
- Keithley model KUSB-3108 data acquisition board. This should be the same A/D board that will be later used in the FWD calibration procedure.
- Push-button 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 five coefficients) that adjusts the indicated load on the universal testing machine to the corrected NIST-traceable calibrated load. The testing machine calibration coefficients shall be entered into the *WinFWDCal* software prior to calibrating a reference load cell.

The Vishay 2310 signal conditioner amplifier should be balanced according to the procedure described in the manufacturer's instruction manual. With the signal input terminals shorted together, at gain 100 the ac noise on the ±10 volt output terminals should 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 Allen screws on the top and the bottom of the load cell to 100 lb.-inch (11.3 N-m). Apply at least 100 conditioning drops on the load cell from the 16,000-lb (72 kN) load level with the FWD. Remove the Allen screws one at a time, apply Locktite to the threads, and torque to precisely 11.3 N-m (100 lb.-in.).

Apply another 100 conditioning drops on the load cell from the 16,000-lb (72 kN) load level with the FWD. Record the unbalanced zero for the load cell after each 25 drops. It should be stable (change less than 1 millivolt) during 25 load cycles. Continue applying additional load cycles until the unbalanced zero stabilizes. Then apply 20 cycles of 24,000 lbs (100 kN) to the load cell with the Universal testing machine.

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 Allen 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 rubber 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 should be connected and powered for at least 60 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 60 minutes. Attach the push-button trigger to the KUSB data acquisition system. Turn on the computer and initialize the *WinFWDCal* program. If a hydraulic universal testing machine is used, turn the pump on and allow it 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 24,000 pounds (100 kN). Apply a nominal load of 24,000 pounds (100 kN) pounds to the load cell three times. Apply the load at a rate of approximately 5,000 to 10,000 pounds (22-44 kN) per minute.

7. Temporarily remove the upper wood/aluminum bearing block. Set the Auto Balance switch on the Vishay 2310 signal conditioner to OFF. Read and record the unbalanced zero voltage using the push-button. If this voltage is in excess of ±5 volts, the load cell may have been damaged by yielding and it should be returned to the manufacturer for repair.

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 24,000 pounds (100 kN), and while it is held relatively constant adjust the Gain knob on the signal conditioner until the signal conditioner output is 9.8 volts or slightly less. Release the load. Record the gain setting.
   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. Apply load at a rate of 1,000 pound (s5 kN) per minute. Use the push-button trigger to record the readings at 1,000 pound (5 kN) intervals up to a maximum load of 24,000 pounds (100 kN). While releasing the load, record a reading at 12,000 pounds (50 kN) and at zero loads.

11. Remove the upper bearing block. Use the push-button to record the signal conditioner calibration voltages for +B and -B. Set the Auto Balance switch to OFF and again record the unbalanced zero voltage. This reading should be within 10 mV of the earlier reading. If it is not, repeat the calibration procedure.

Data Analysis

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

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

Figure 25. Equation. Load cell calibration algorithm.

where *Y* represents the load, *V* the voltage of the load cell, and where the coefficients A_i are determined by the regression. Evaluate the results according to the following acceptance criteria.

- The standard error should be less than ±20 pounds (0.1 kN).
- Each of the coefficients should be statistically significant.

After completion of 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 completed.

The final set of calibration coefficients should be valuated according to the above two criteria. In addition, the three sets of data should be random, neither steadily increasing nor steadily decreasing.

Enter the Coefficients in *WinFWDCal*

The load cell coefficients should be entered in the *WinFWDCal* configuration file. Follow the instructions in the Load Cell Setup section of the *WinFWDCal Software User's Guide*[(3)]. Any of the coefficients that are <u>not</u> found to be significant should be entered as 0.0.

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

REFERENCES

1. Strategic Highway Research Program. (1994). "SHRP/LTPP FWD Calibration Protocol." Transportation Research Board, Washington , DC.

2. Cornell Local Roads Program. (2007). *WinFWDCal.* ver 1.1.2, Cornell Local Roads Program, Ithaca, NY.

3. Cornell Local Roads Program. (2007). *WinFWDCal Software User's Guide*, Cornell Local Roads Program, Ithaca, NY.

4. Orr, D. P., and Irwin, L. H. (2007). "FWD Calibration Center and Operational Improvements: Final Report." Federal Highway Administration, Washington, DC.

APPENDIX II. SPECIFICATIONS AND DRAWINGS

SPECIFICATIONS

1. General specifications

1.1. Description

FWD Calibration Hardware Set includes 1 accelerometer box assembly, 1 geophone calibration stand assembly, 1 seismometer calibration stand assembly, and 1 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 10 shows a list of assembly drawings for each assembly.

Table 10. Parts Required for 1 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

* 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 10).

1.3. Manufacturing Requirements/Conflicts

The contractor shall provide all materials needed to manufacture 1 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.

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.

1.5. 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.

1.6. Loctite

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

1.7. 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 s7 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.

1.8. Method of Payment

Payment shall be authorized upon acceptance of the complete order.

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

2.1. 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.

2.2. Materials

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

2.3. Manufacturing Requirements

The accelerometer box top and bottom, 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.

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

3.1. Description

The Ball Joint Anchor Assembly is the means by which the calibration stands are coupled to the test pad during FWD calibration. The clamp provides a solid mechanical connection to the calibration stand and the Techno/Sommer KG60 ball joint provides some rotational freedom making the stands easier to use as well as providing for some moment compensation.

3.2. Materials

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

3.3. Manufacturing Requirements

Upon delivery, the customer 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

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

4.1. Description

The Geophone Calibration Stand Assembly is designed to hold up to 10 geophones from the Dynatest, Carl Bro, 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.

4.2. Materials

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

4.3. Manufacturing Requirements

Prior to welding the stand, the parts 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 Loctiting the connector pin in place.

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

5.1. 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.

5.2. Materials

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

5.3. Manufacturing Requirements

Prior to welding the stand, the parts 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 Loctiting the connector pin in place.

6. Geophone Adapter Specifications

6.1. 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.

6.2. Materials

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

6.3. Manufacturing Requirements

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

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, and Data Acquisition Cables.

Table 11. Complete drawing list.

Drawing Number	Part Name	Revision
CLRP-AB01	Accelerometer Box Assembly	C
CLRP-AB02	Accelerometer Box Bottom	E
CLRP-AB03	Accelerometer Box Top	G
CLRP-AB04	Calibration Platter	E
CLRP-AB05	Accelerometer Wiring	C
CLRP-BJ01	Ball Joint Anchor Assembly	B
CLRP-BJ02	Clamp	C
CLRP-BJ03	Clamp Base	D
CLRP-BJ04	Base Bar	D
CLRP-BJ05	Rest Stop	D
CLRP-GCS01	Geophone Stand Assembly	G
CLRP-GCS02	Geophone Stand Side Rail	E
CLRP-GCS03	Geophone Stand Top Shelf	C
CLRP-GCS04	Geophone Stand Bottom Shelf	C
CLRP-GCS05	Geophone Stand Sensor Shelf	E

Drawing Number	Part Name	Revision
CLRP-GCS06	Geophone Stand Accelerometer Shelf	E
CLRP-GCS07	Geophone Stand Handle Holder	F
CLRP-GCS08	Geophone Stand Connector Pin	B
CLRP-SCS01	Seismometer Stand Assembly	E
CLRP-SCS02	Seismometer Stand Side Rail	B
CLRP-SCS03	Seismometer Stand Top Shelf	B
CLRP-SCS04	Seismometer Stand Sensor Shelf	D
CLRP-SCS05	Seismometer Stand Standoff	E
CLRP-SCS06	Seismometer Stand Bottom Shelf	B
CLRP-SCS07	Seismometer Stand Handle Holder	F
CLRP-SCS08	Seismometer Stand Connector Pin	B
CLRP-SCS09	Seismometer Stand Shelf Subassembly	C
CLRP-SCS10	Seismometer Stand Accelerometer Shelf	D
CLRP-SCS11	Seismometer Stand Accelerometer Shelf Subassembly	B
CLRP-GA01	Geophone Adapter Assemblies	B
CLRP-GA02	Carl Bro Adapter	E
CLRP-GA03	JILS Adapter	F
CLRP-DAQ01	Vishay to KUSB Cable	C
CLRP-DAQ02	Vishay to Load Cell DAQ Cable	B
CLRP-DAQ03	Accelerometer Signal Cable	C
CLRP-DAQ04	Pushbutton to KUSB DAQ Cable	C

Current as of: 03/27/2007

ACCELEROMETER BOX

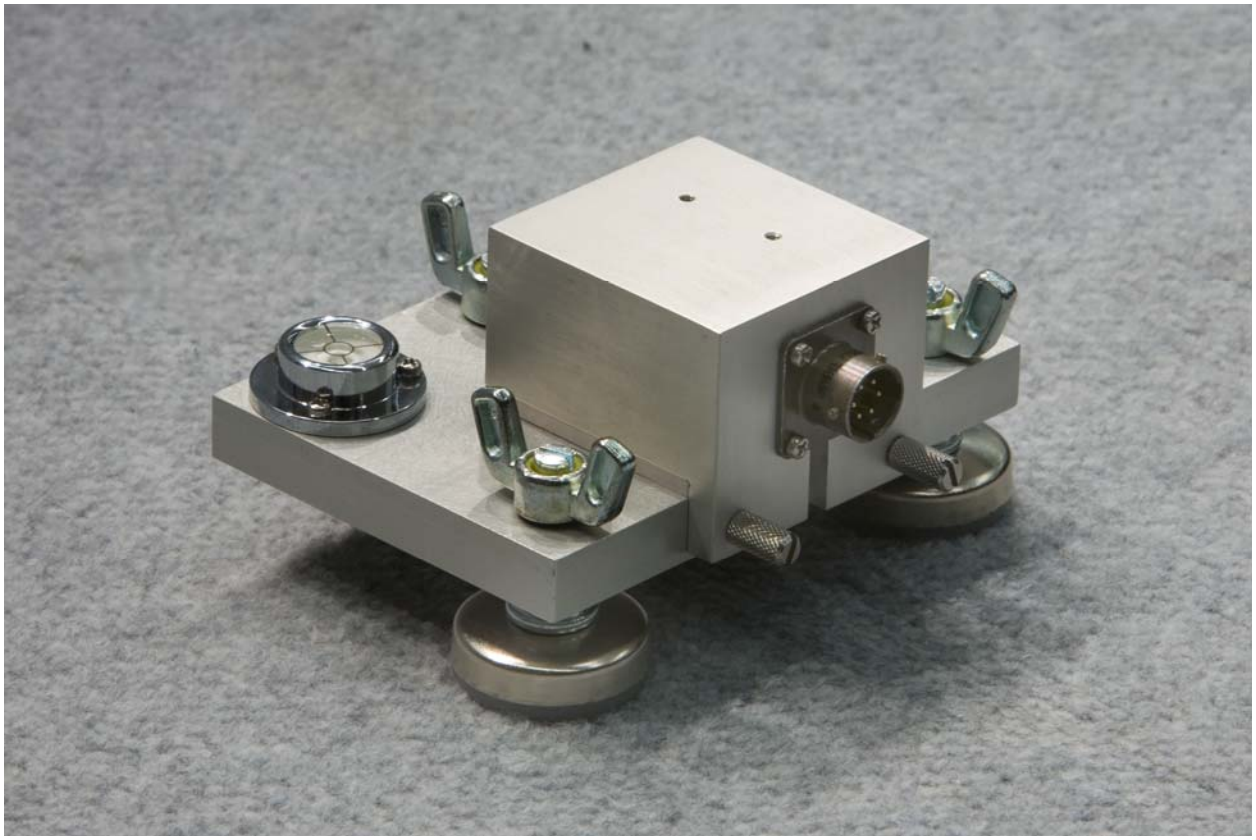

Figure 26. Photo. Accelerometer box.

BM-AB Accelerometer Box Bill of Materials

Table 12. 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 13. 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	Bullseye 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 lb 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 14. 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

Vendor	Web site	Notes
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 15. Hardware costs for accelerometer box.

Part	Quantity	Supplier	Cost*	Notes
Materials and machining	1	Incodema	$515.00	
Accelerometer (±5g)	1	Silicon Designs	$560.00	
Misc. Hardware	1		$35.00	

*Indicates the cost for the Cornell team.

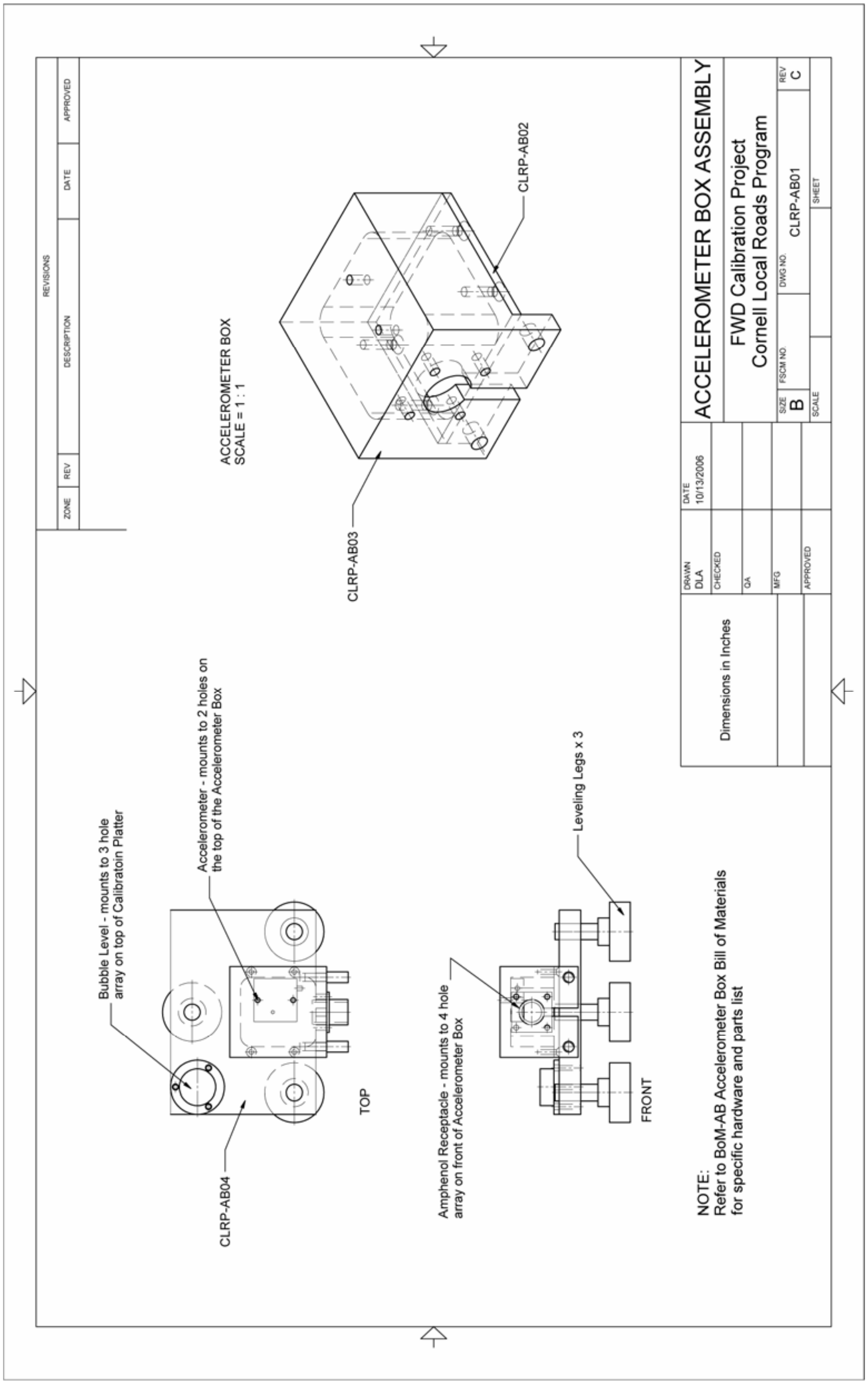

Figure 27. Drawing. CLRP-AB01 Accelerometer Box Assembly.

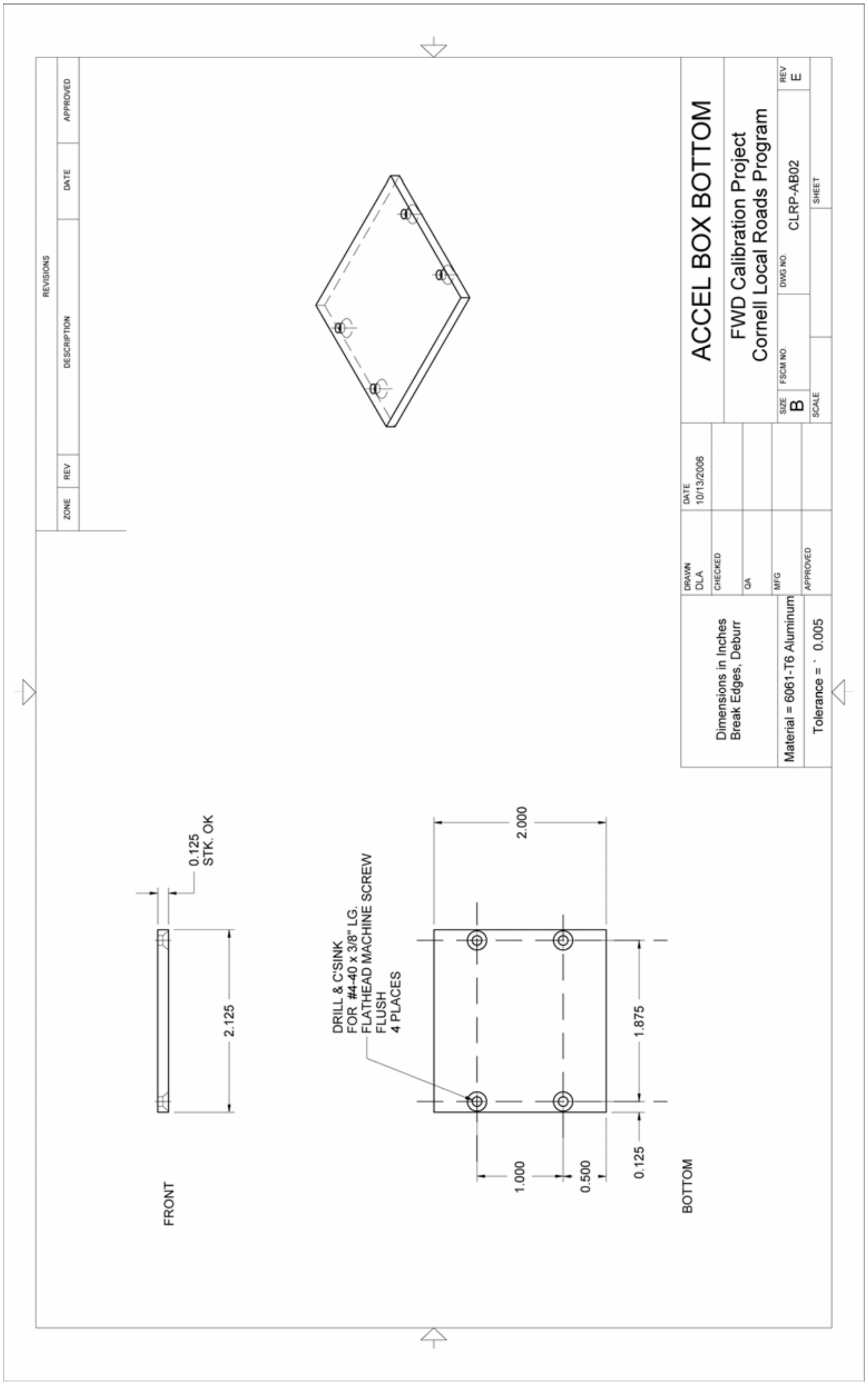

Figure 28. Drawing. CLRP-AB02 Accelerometer Box Bottom.

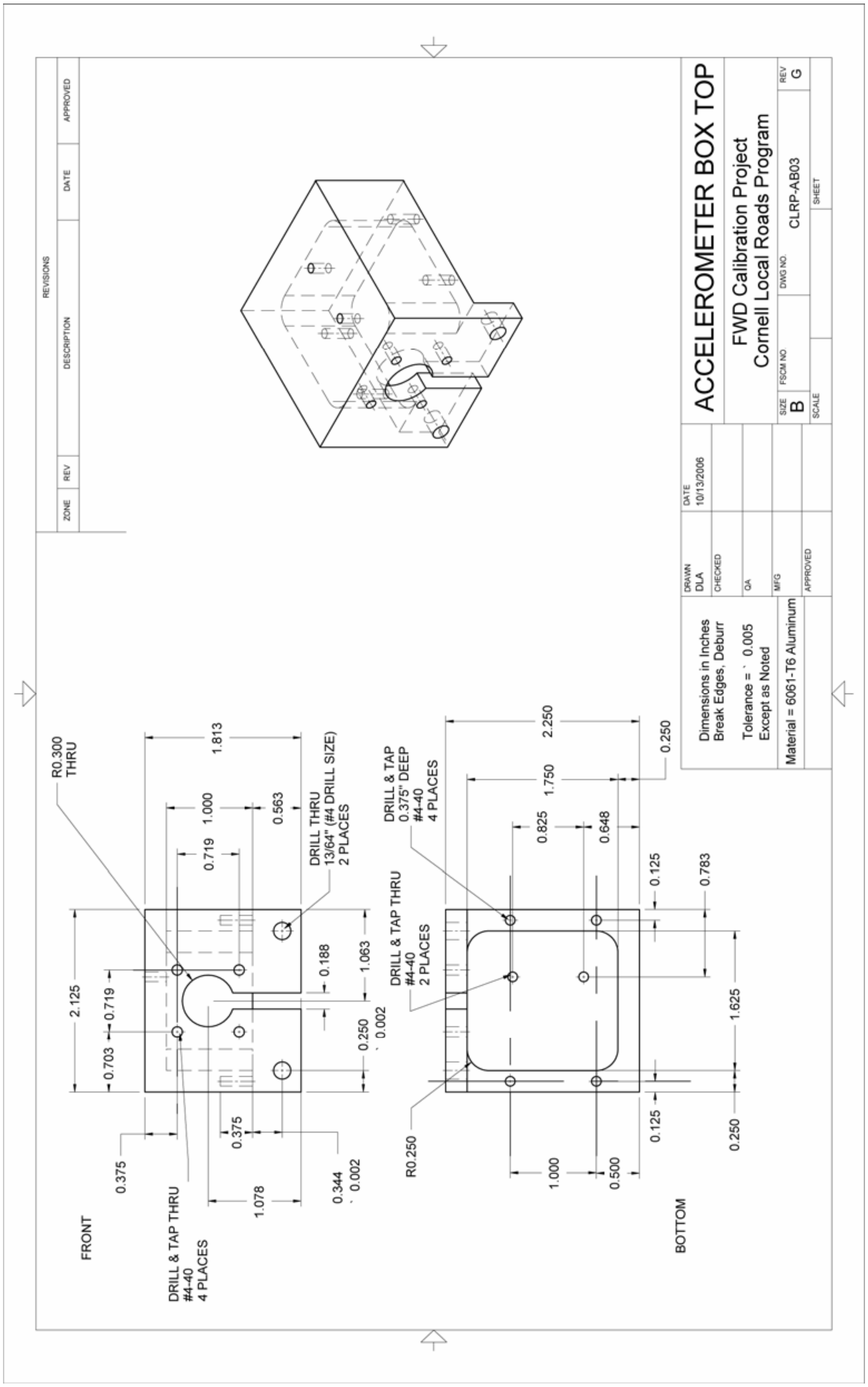

Figure 29. Drawing. CLRP-AB03 Accelerometer Box Top.

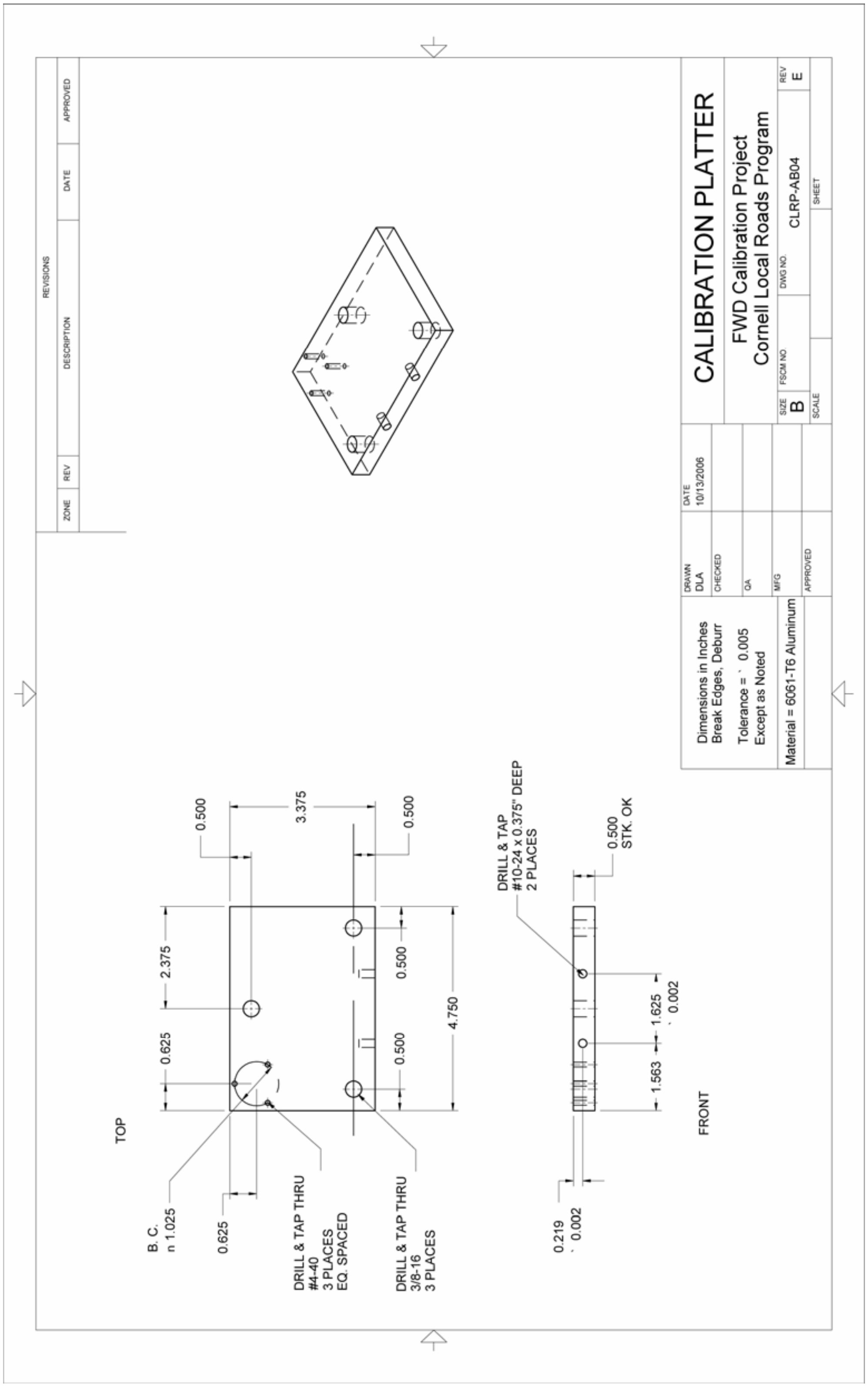

Figure 30. Drawing. CLRP-AB04 Calibration Platter.

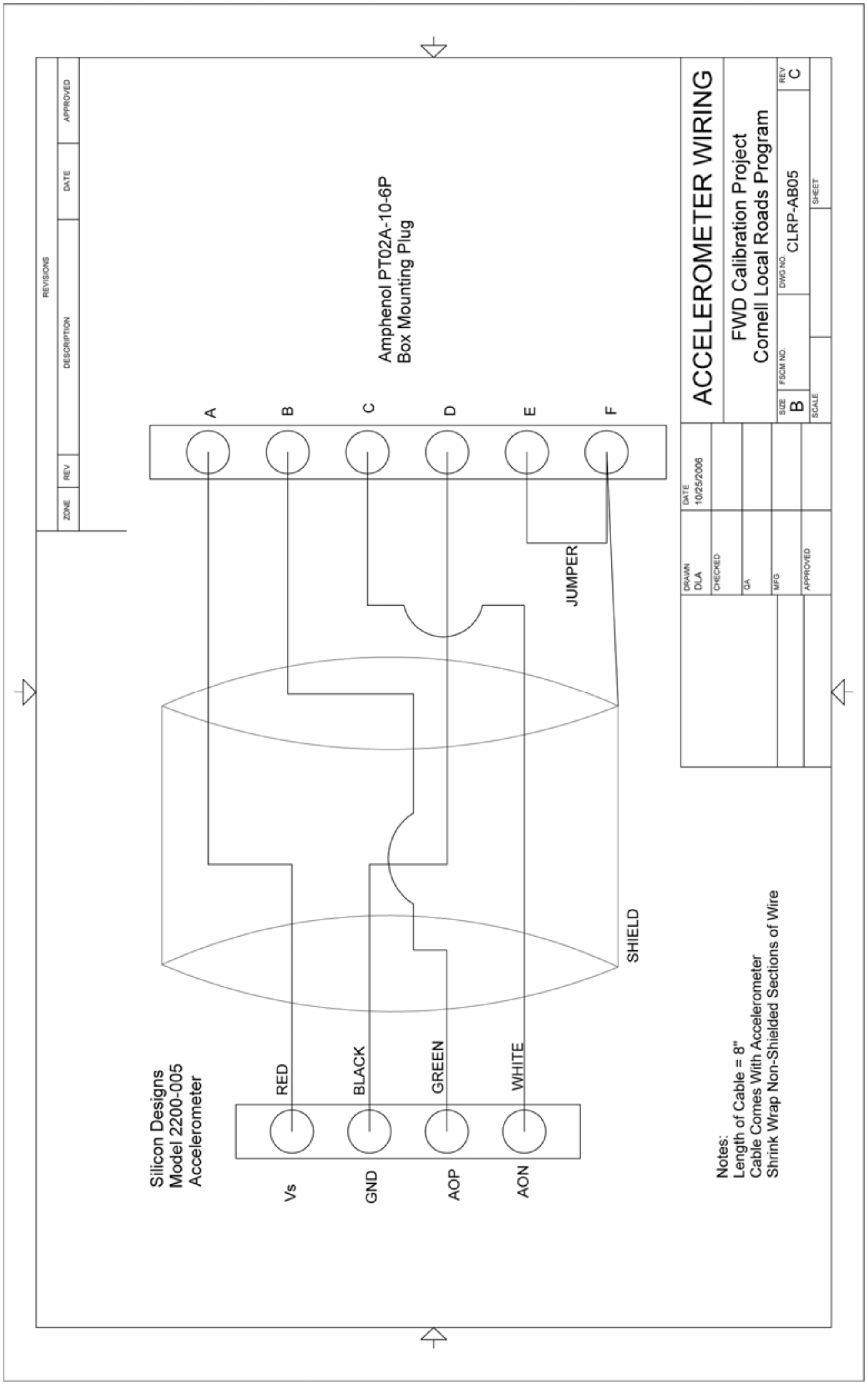

Figure 31. Drawing. CLRP-AB05 Accelerometer Wiring.

BALL JOINT ANCHOR

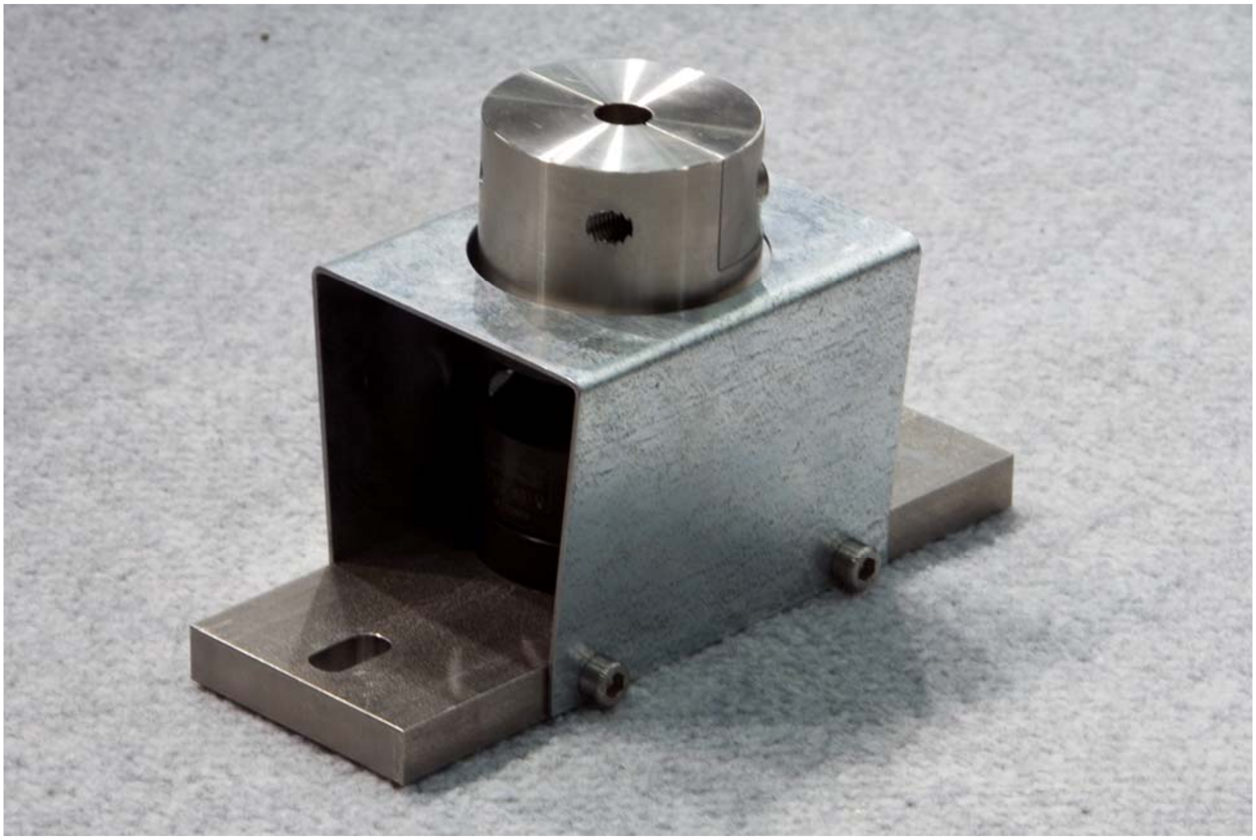

Figure 32. Photo. Ball joint anchor.

BM-BJ Ball Joint Anchor Bill of Materials

Table 16. 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 17. 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 18. 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 19. Hardware costs for ball joint anchor.

Part	Quantity	Supplier	Cost*	Notes
Materials and machining	1	Incodema	$425.00	
Techno/Sommer KG60 Ball Joint	1	Techno/Sommer	$124.75	
Misc. Hardware	1		$15.00	

*Indicates the cost for the Cornell team.

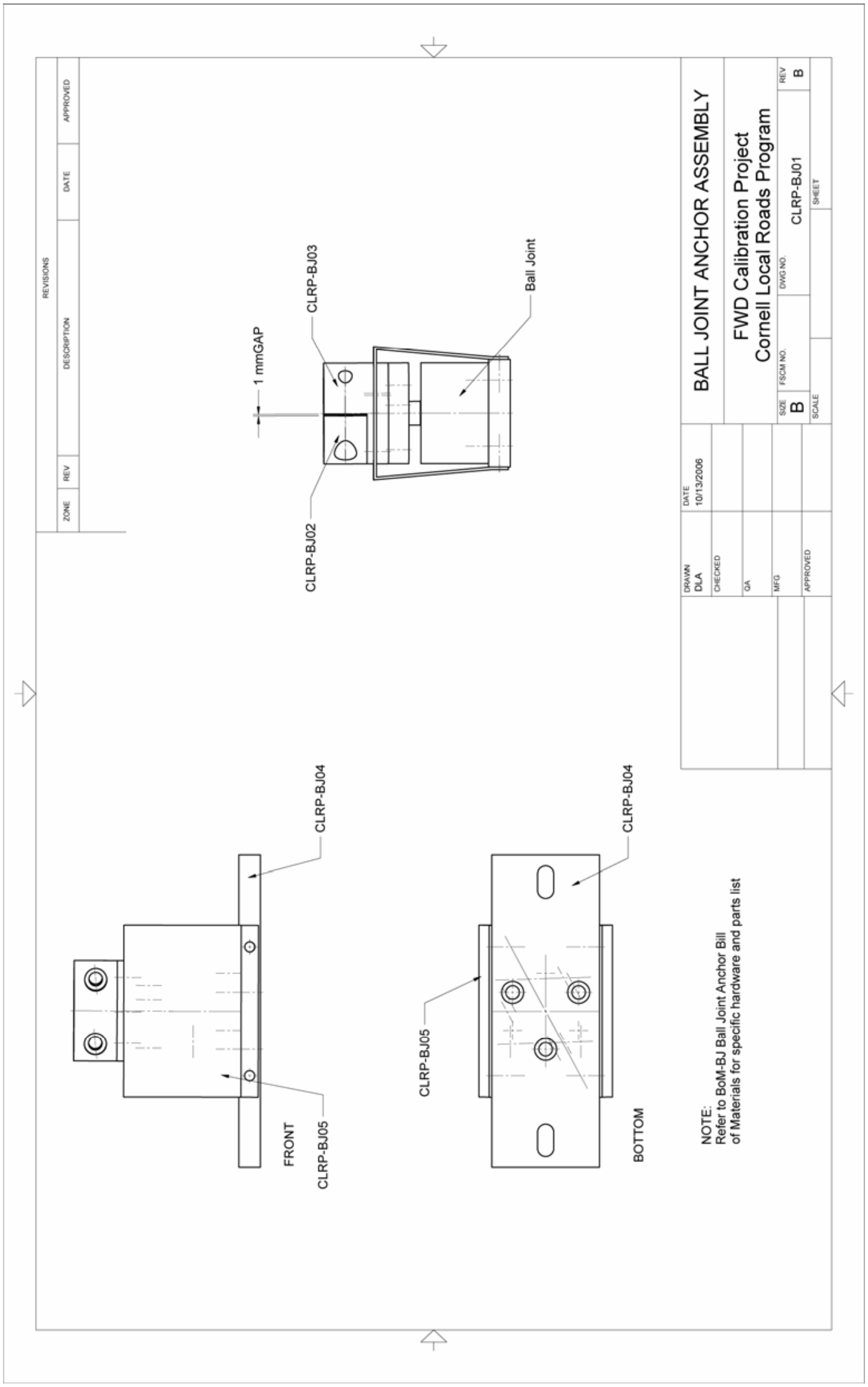

Figure 33. Drawing. CLRP-BJ01 Ball Joint Anchor Assembly.

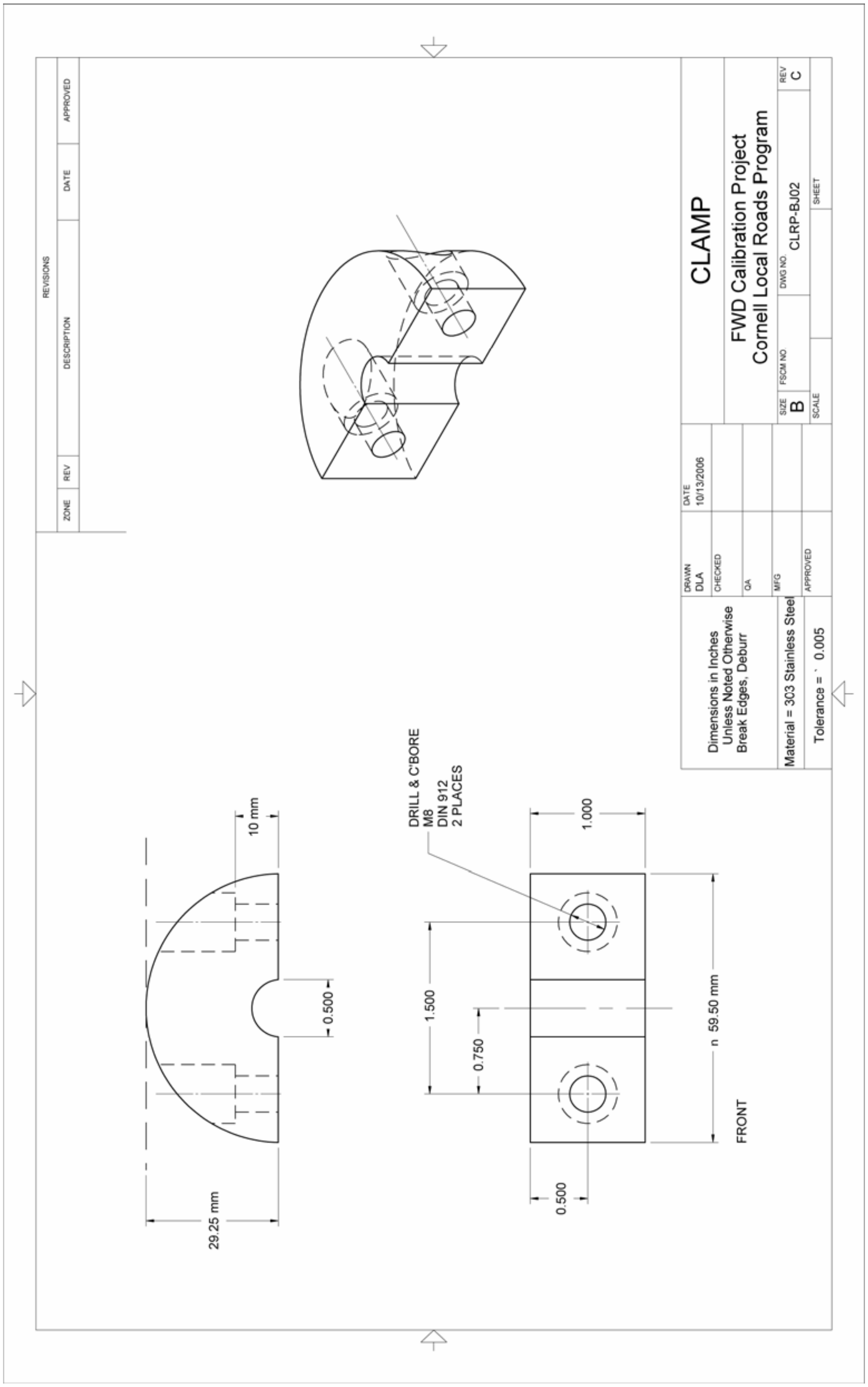

Figure 34. Drawing. CLRP-BJ02 Clamp.

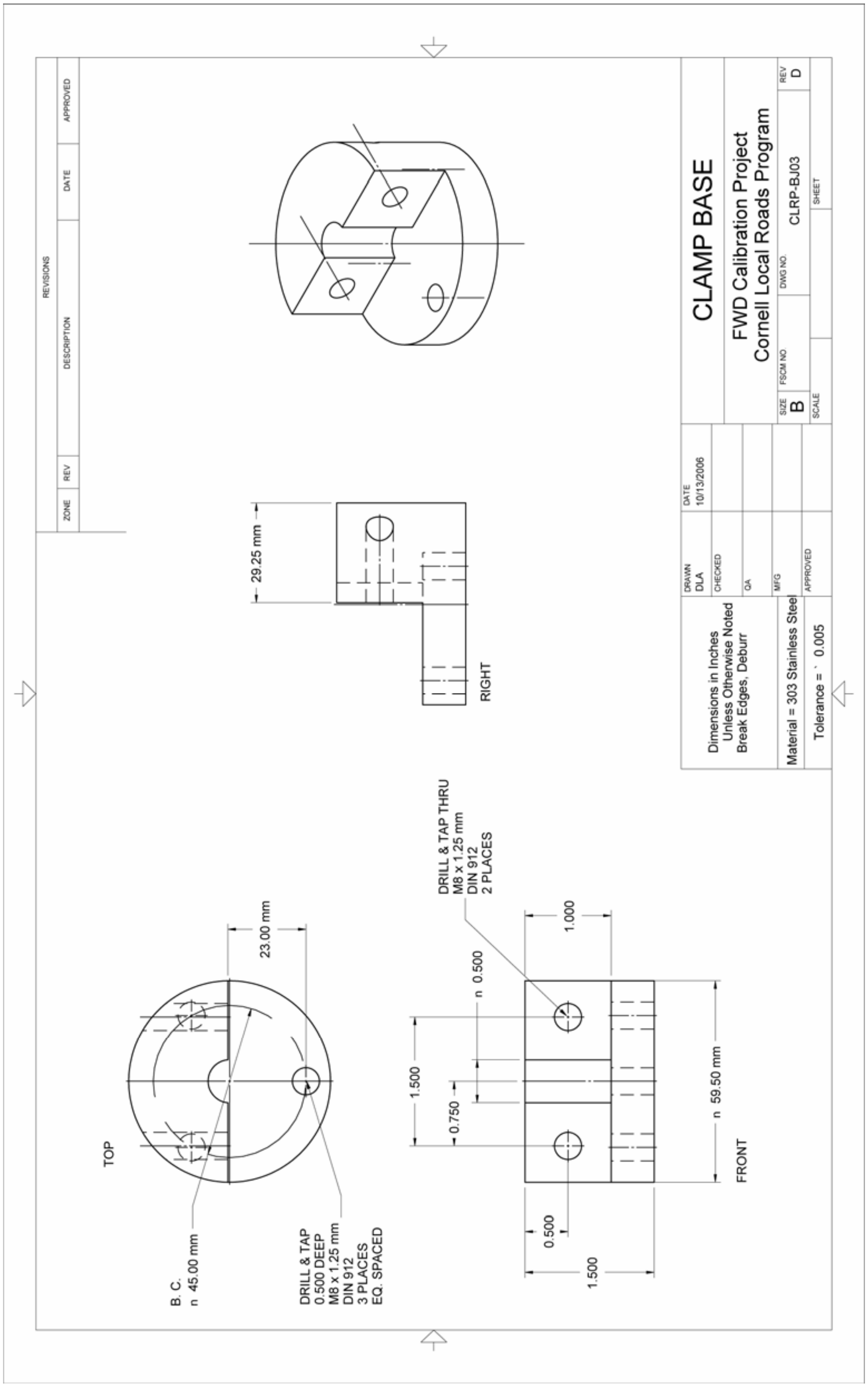

Figure 35. Drawing. CLRP-BJ03 Clamp Base.

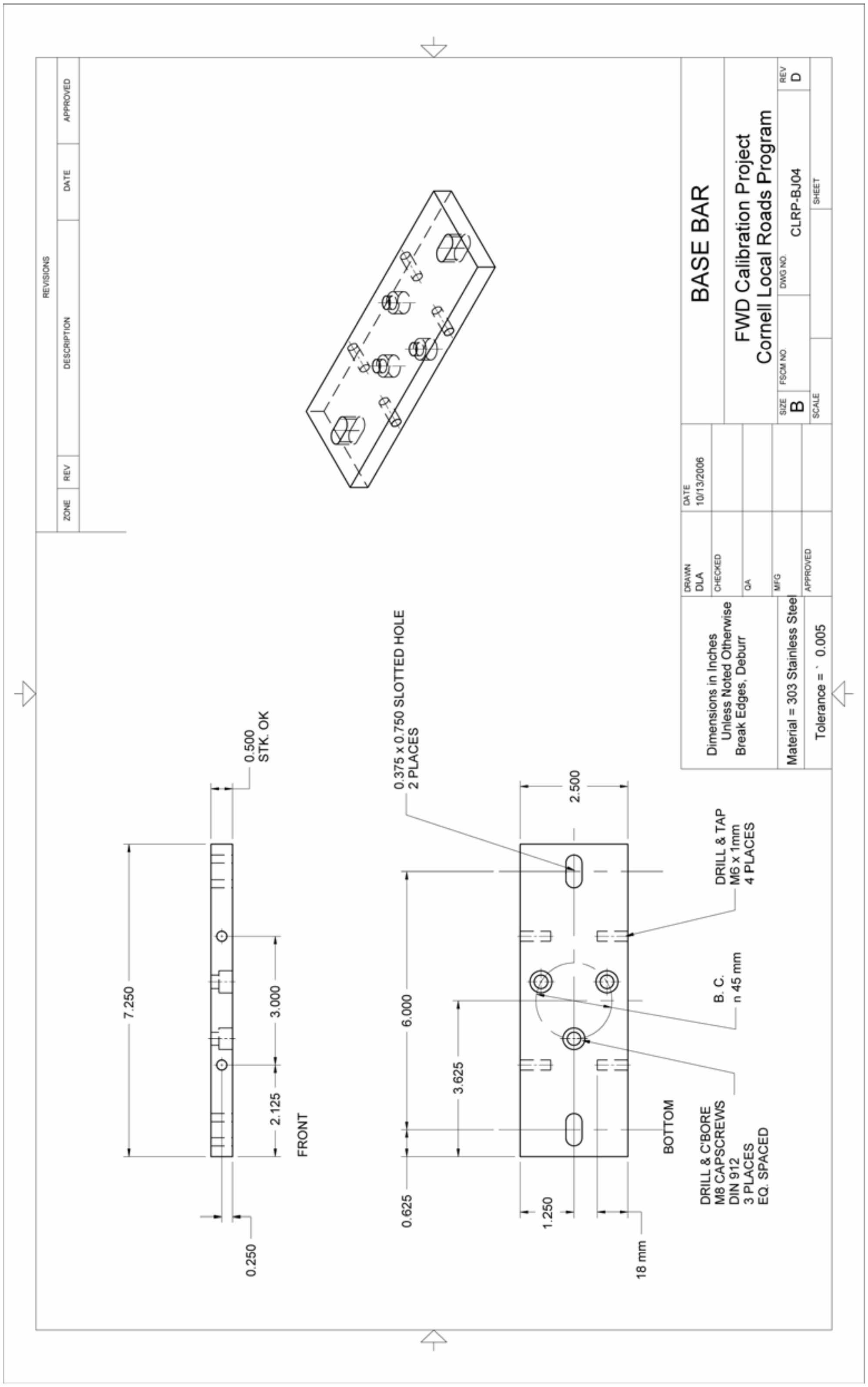

Figure 36. Drawing. CLRP-BJ04 Base Bar.

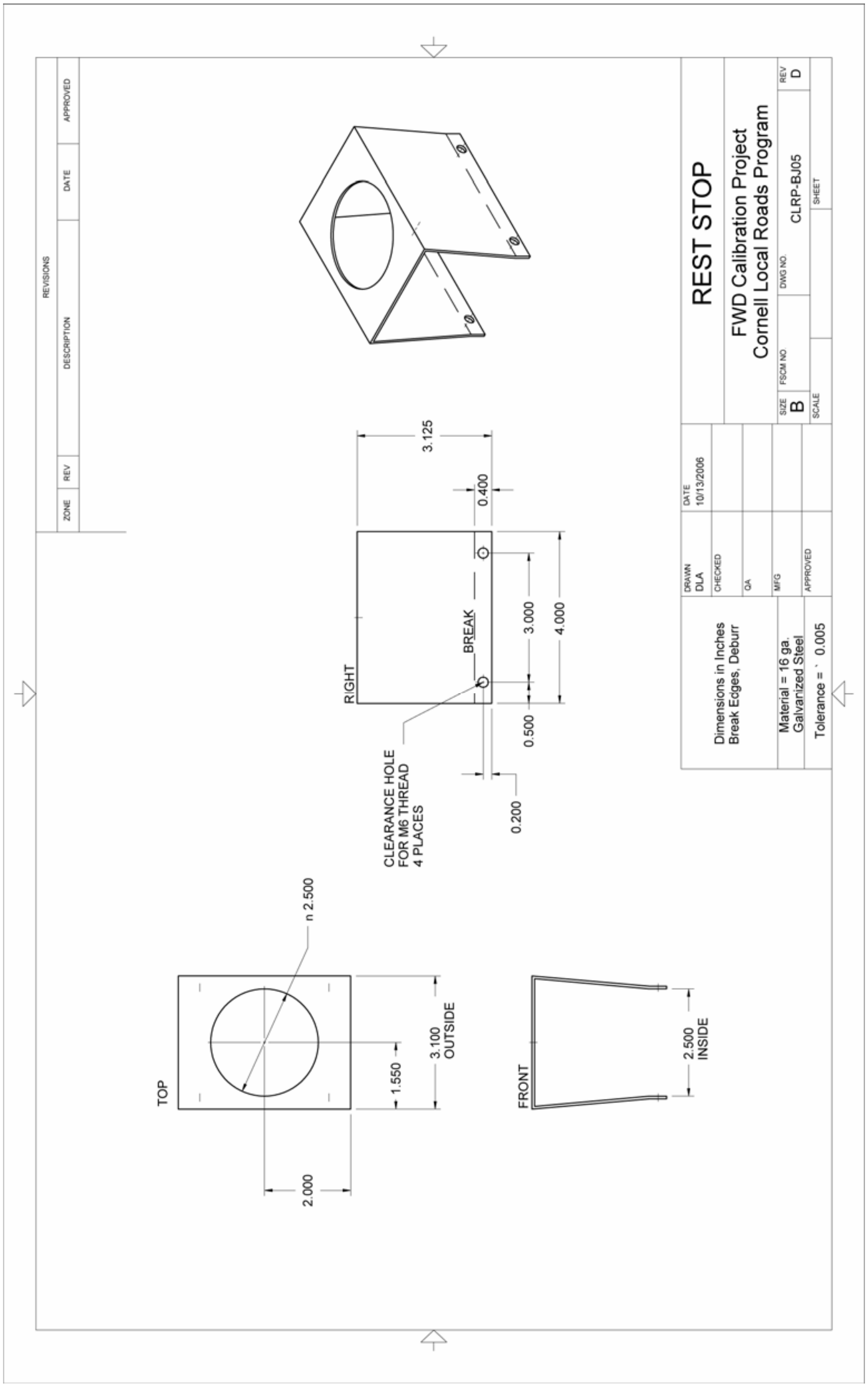

Figure 37. Drawing. CLRP BJ05 Rest Stop.

GEOPHONE CALIBRATION STAND

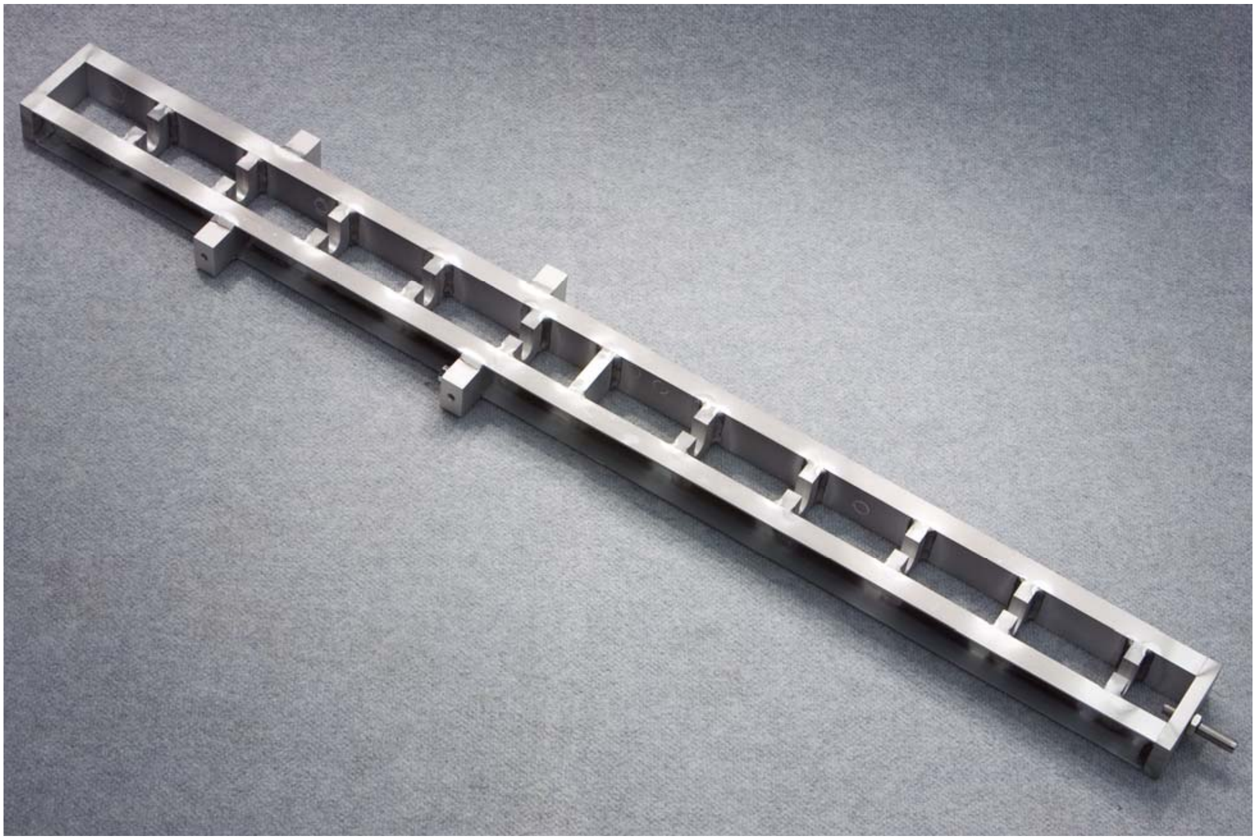

Figure 38. Photo. Geophone calibration stand.

BM-GCS Geophone Calibration Stand Bill of Materials

Table 20. 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 21. 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 Bullseye 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 22. 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 23. Hardware costs for geophone calibration stand.

Part	Quantity	Supplier	Cost*	Notes
Materials and machining	1	Incodema	$750.00	
Misc. hardware	1		$20.00	

*Indicates the cost for the Cornell team.

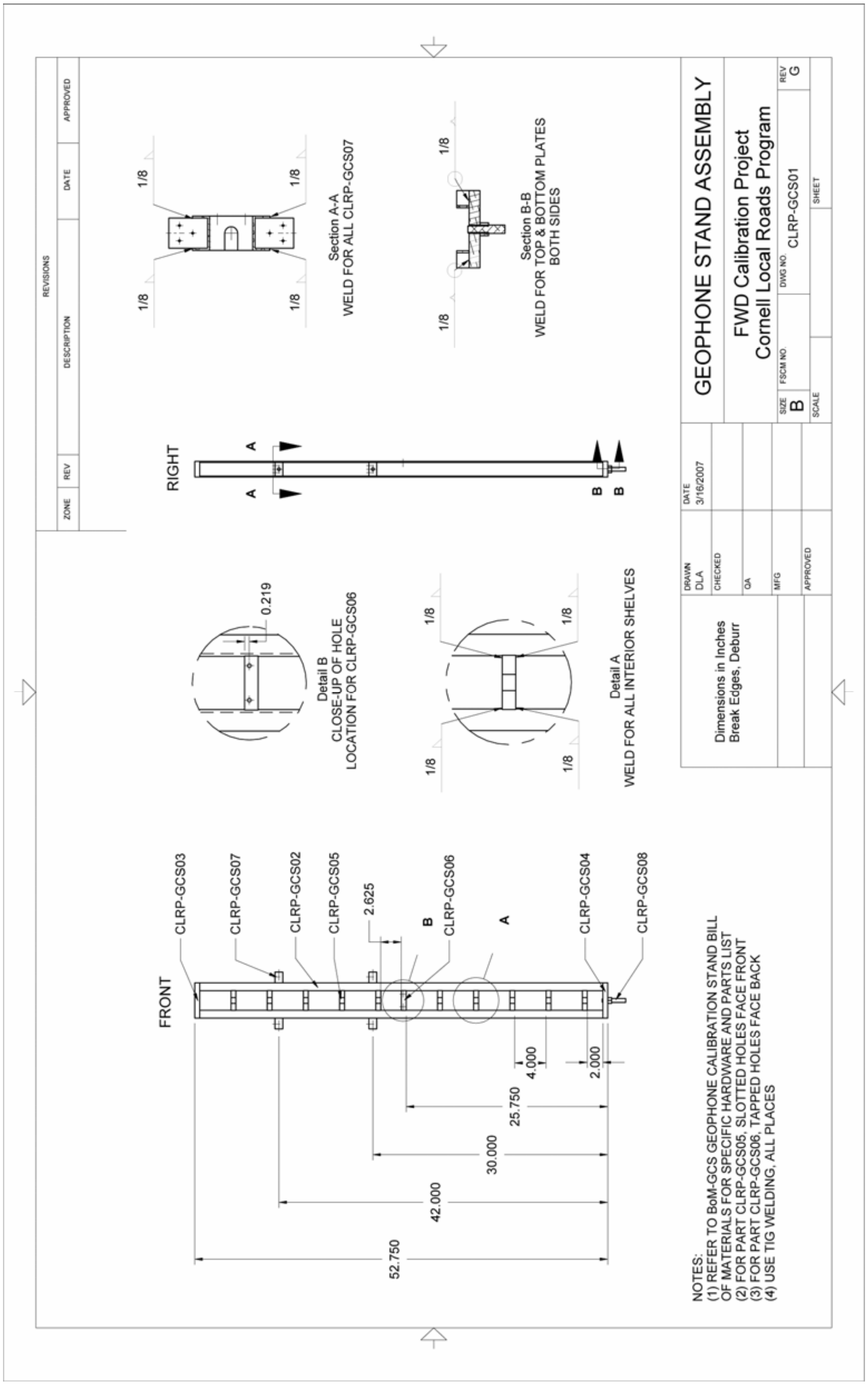

Figure 39. Drawing. CLRP-GCS01 Geophone Stand Assembly.

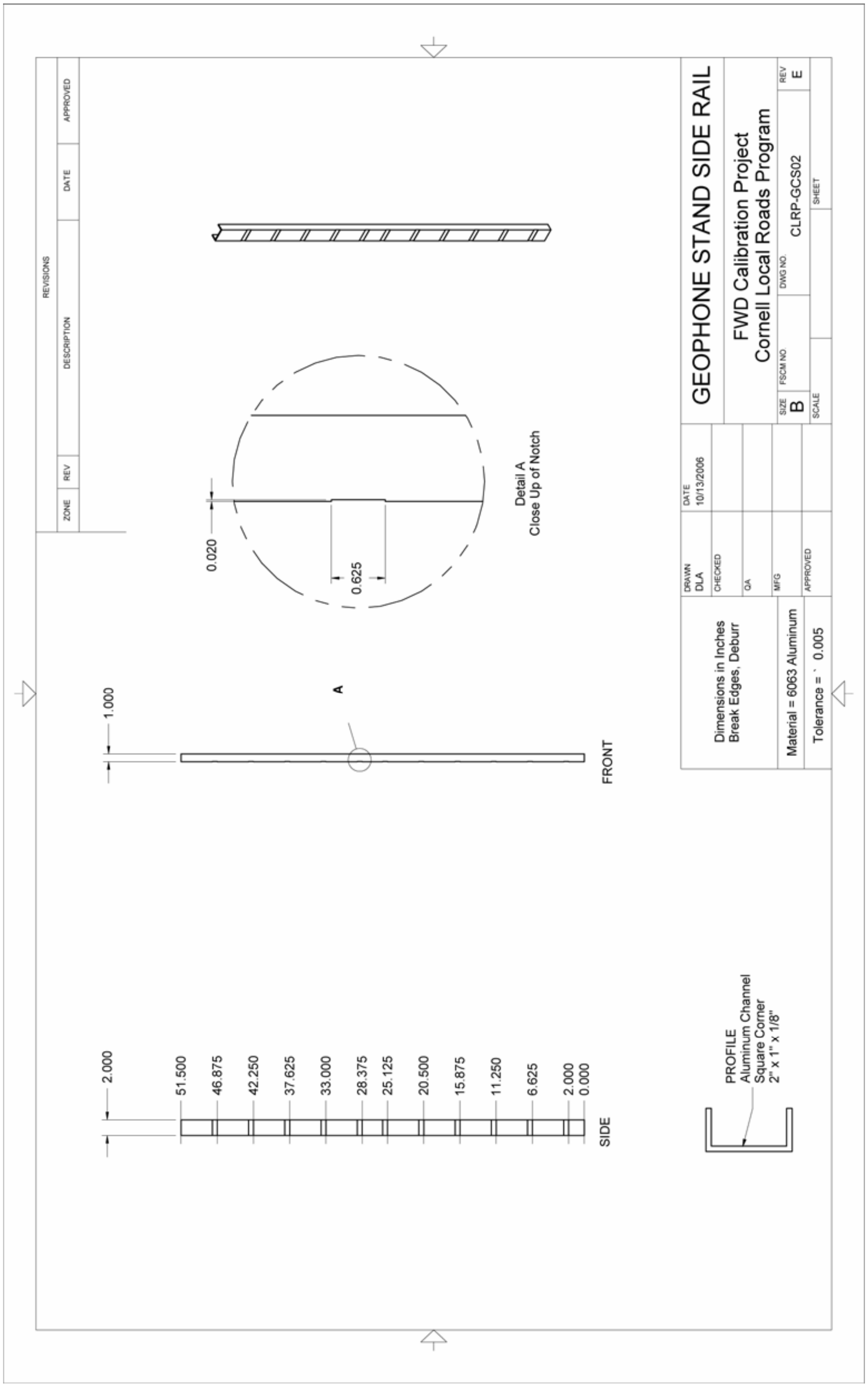

Figure 40. Drawing. CLRP-GCS02 Geophone Stand Side Rail.

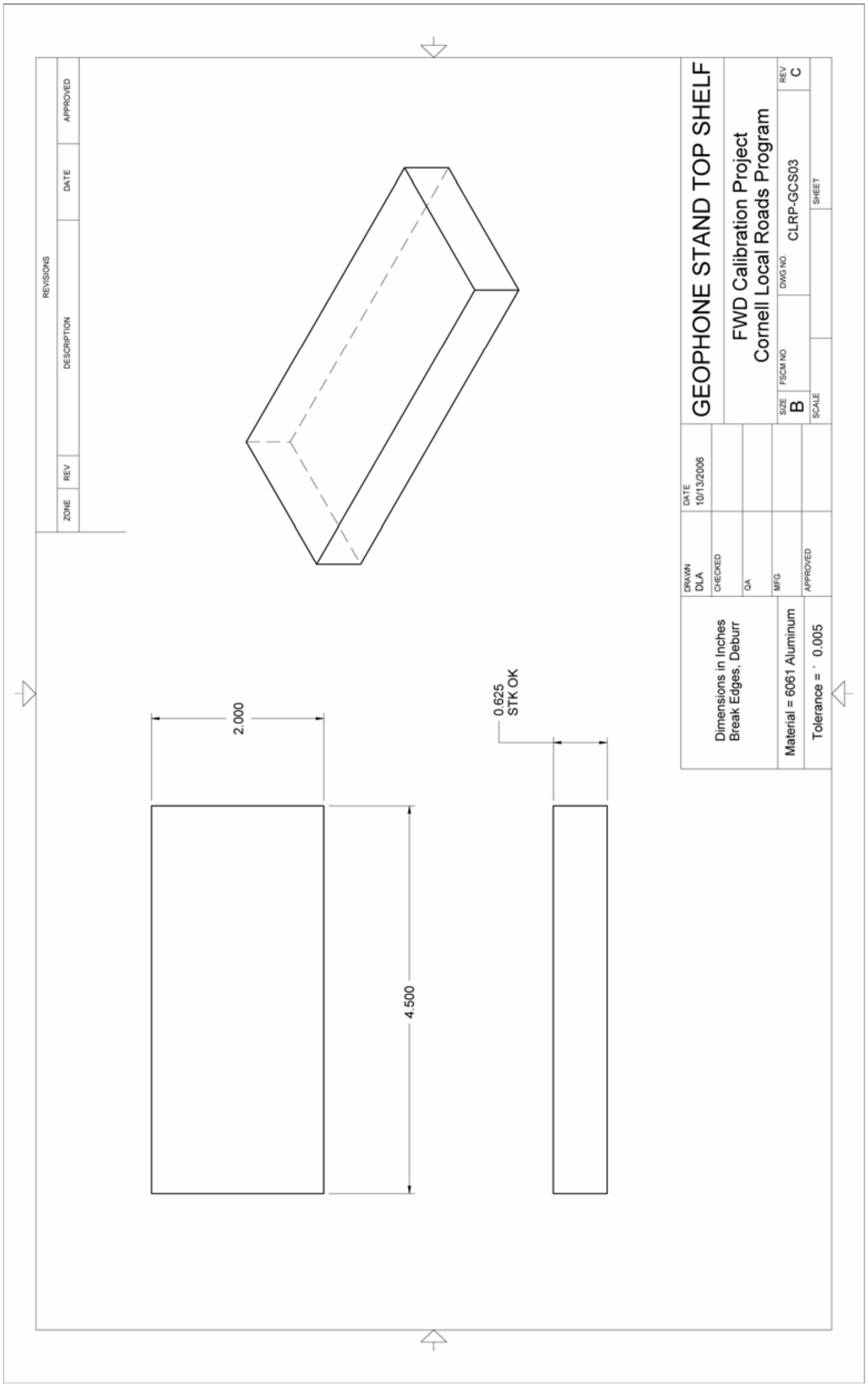

Figure 41. Drawing. CLRP-GCS03 Geophone Top Shelf.

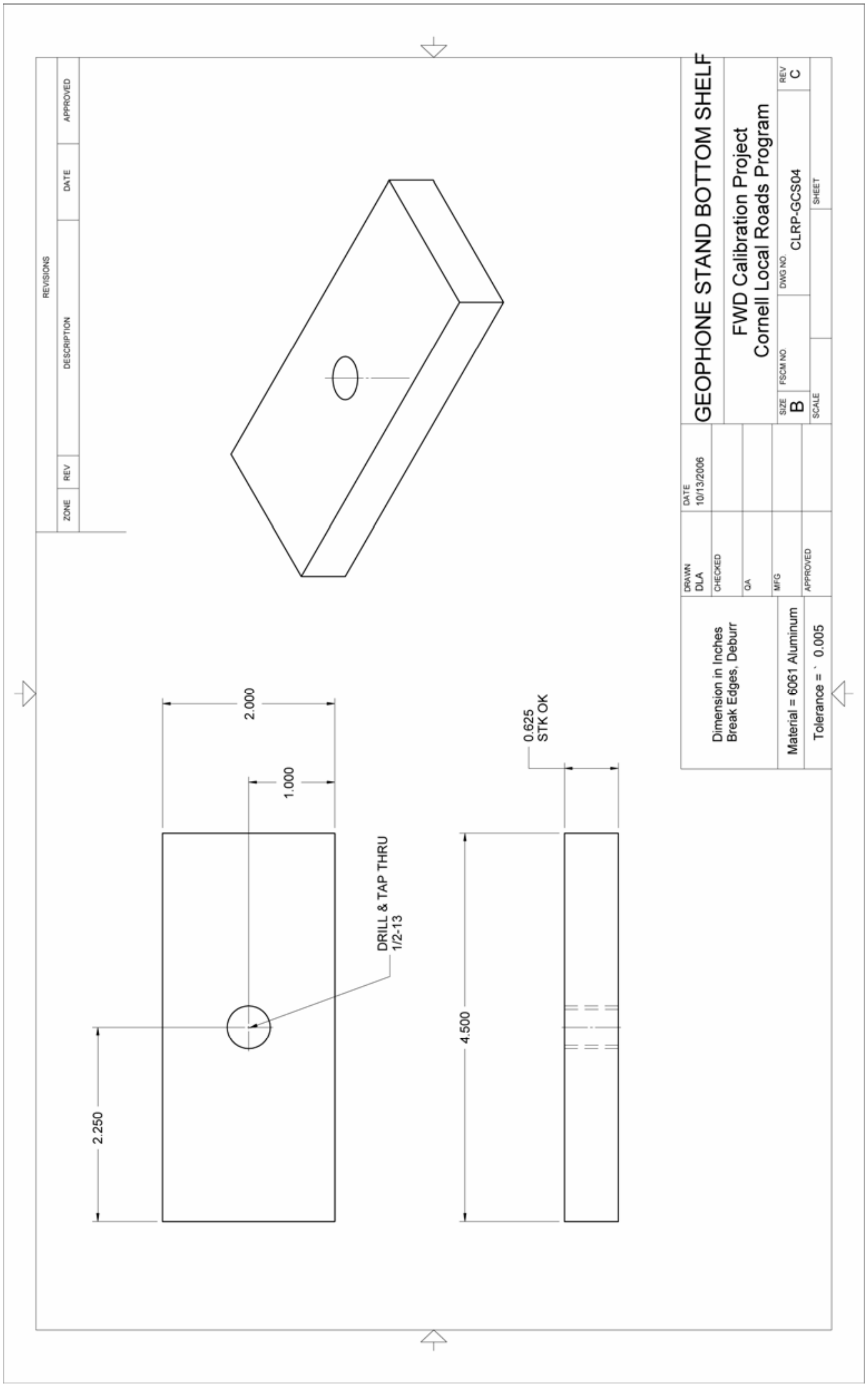

Figure 42. Drawing. CLRP-GCS04 Geophone Stand Bottom Shelf.

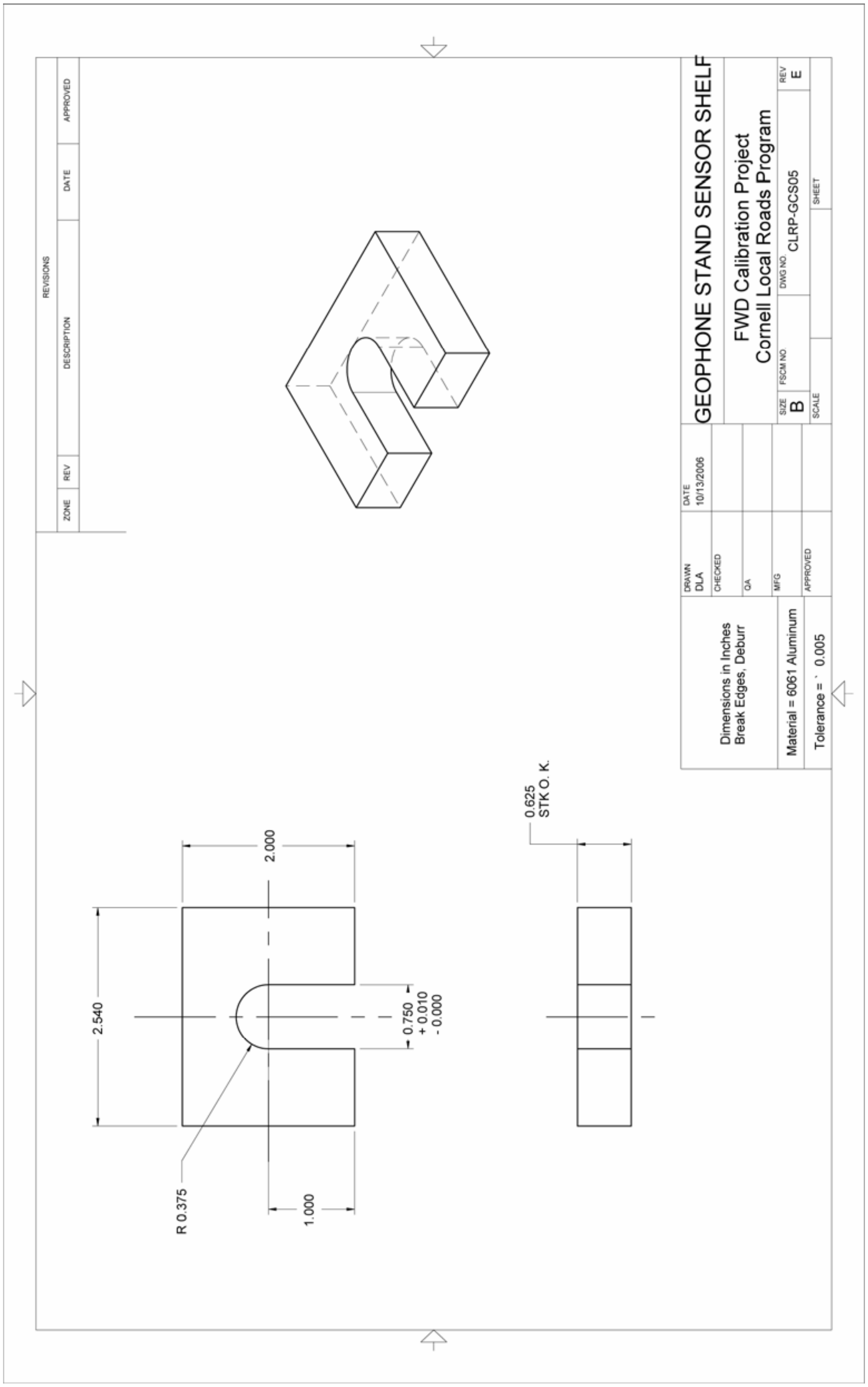

Figure 43. Drawing. CLRP-GCS05 Geophone Stand Sensor Shelf.

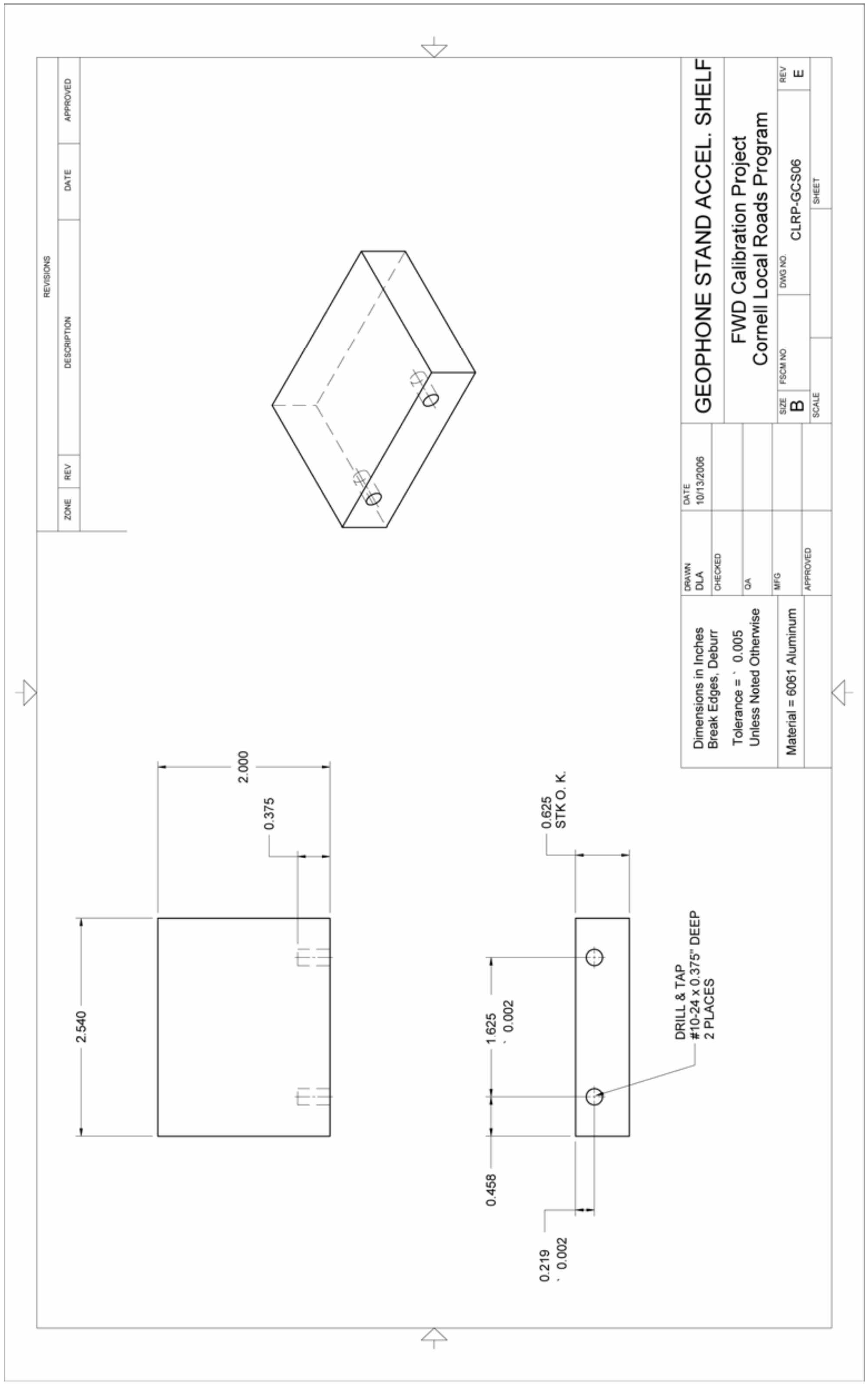

Figure 44. Drawing. CLRP-GCS06 Geophone Stand Accelerometer Shelf.

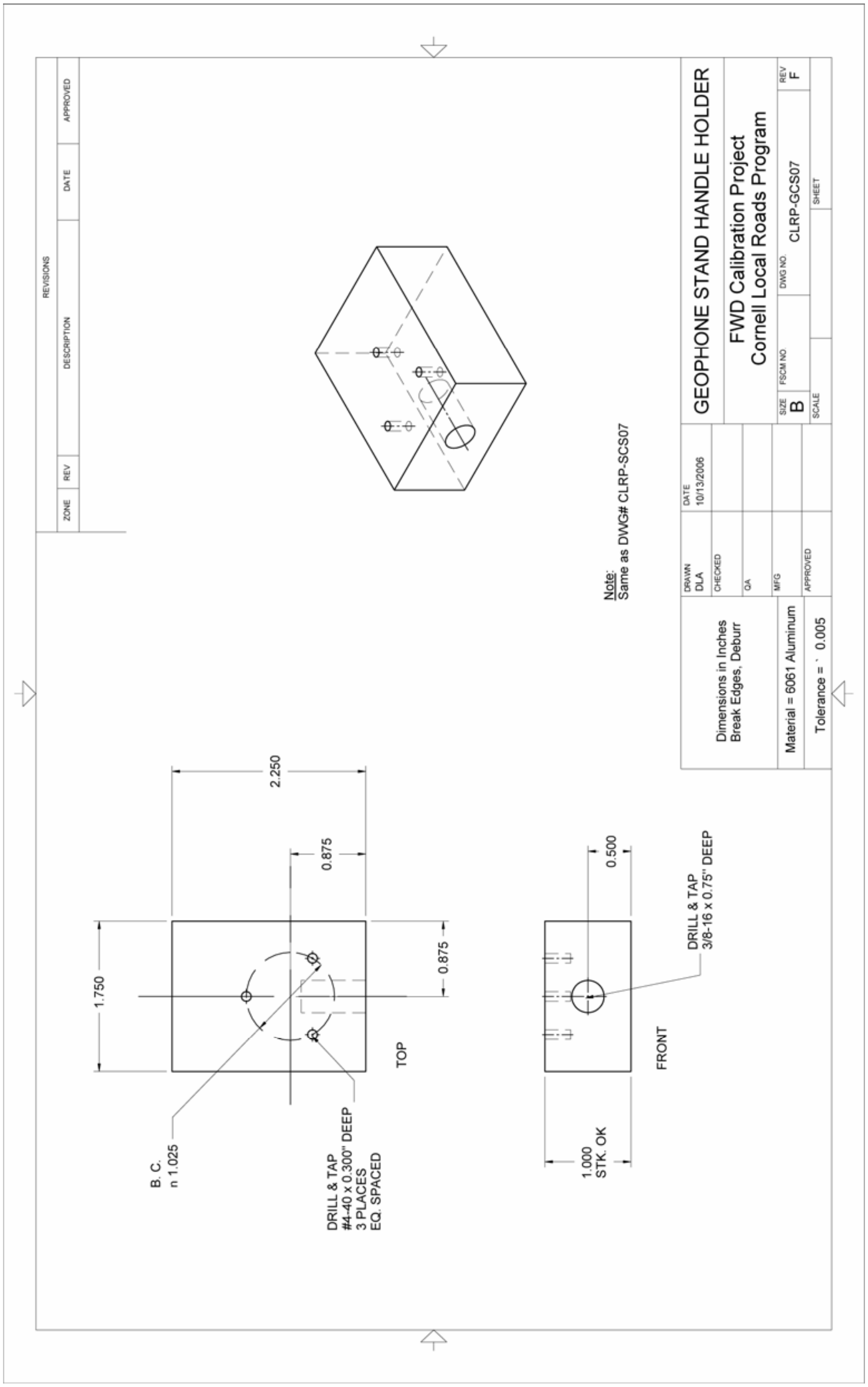

Figure 45. Drawing. CLRP-GCS07 Geophone Stand Handle Holder.

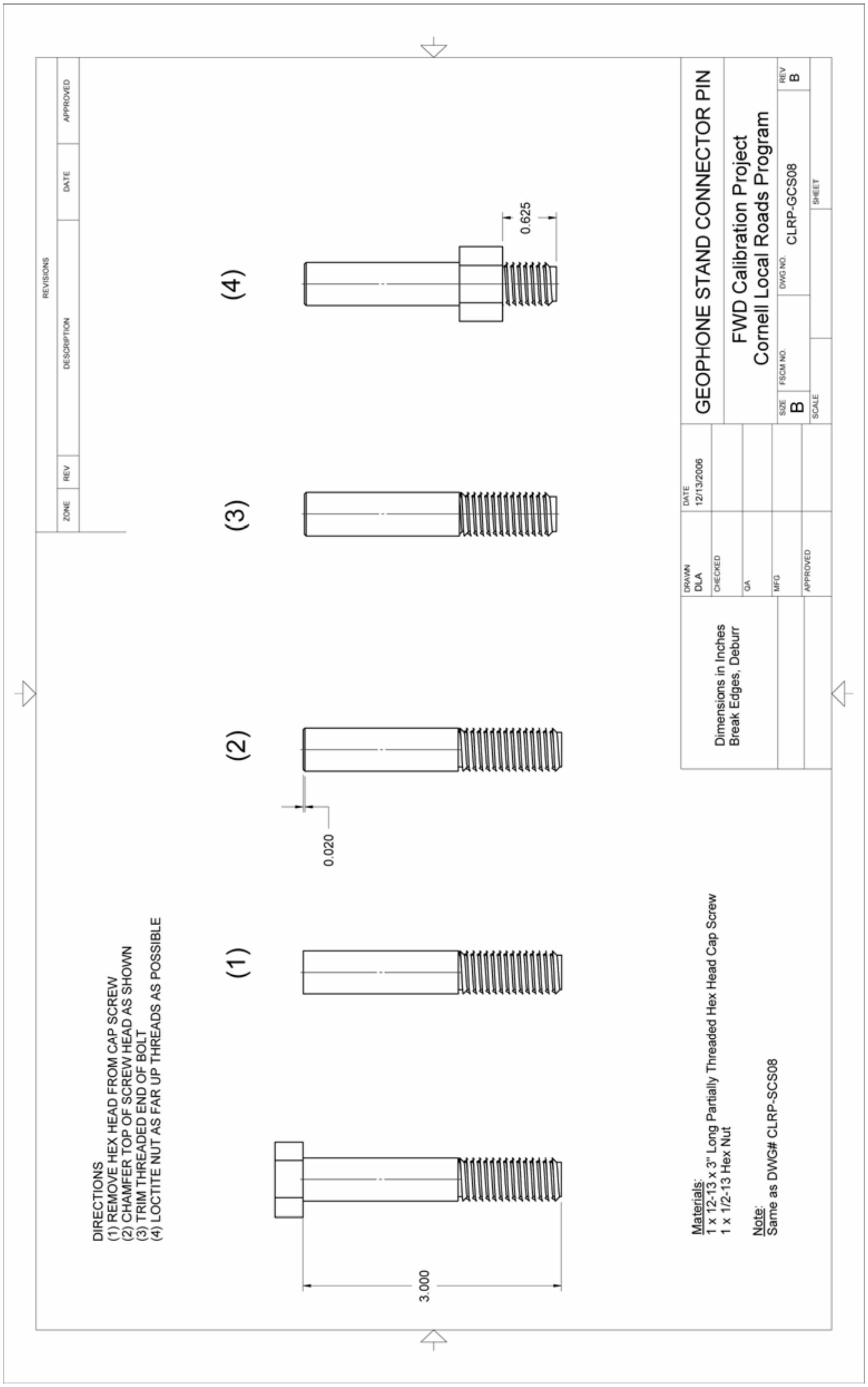

Figure 46. Drawing. CLRP-GCS08 Geophone Stand Connector Pin.

SEISMOMETER CALIBRATION STAND

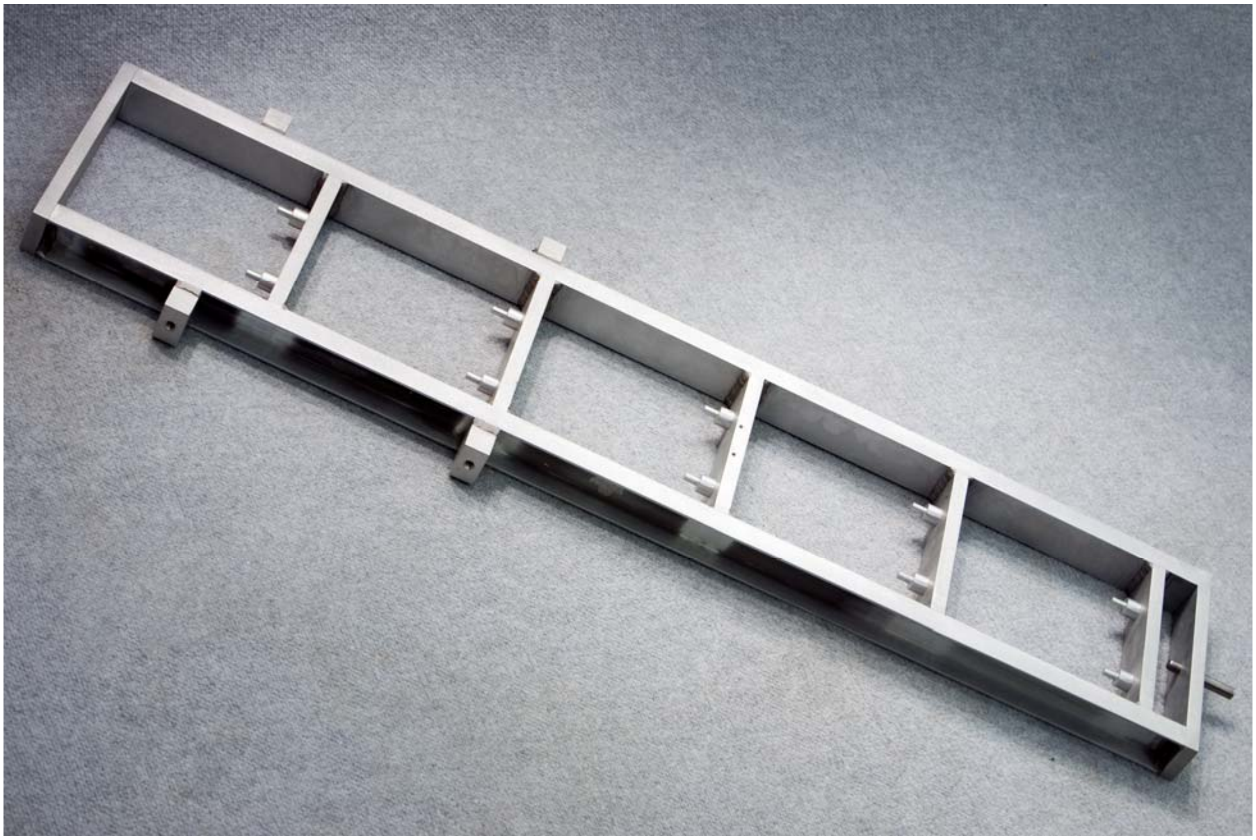

Figure 47. Photo. Seismometer calibration stand.

BM-SCS Seismometer Calibration Stand Bill of Materials

Table 24. 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 25. 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 Bullseye 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 26. 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 27. Hardware costs for seismometer calibration stand assembly.

Part	Quantity	Supplier	Cost*	Notes
Materials and machining	1	Incodema	$750.00	
Misc. hardware	1		$20.00	

*Indicates the cost for the Cornell team.

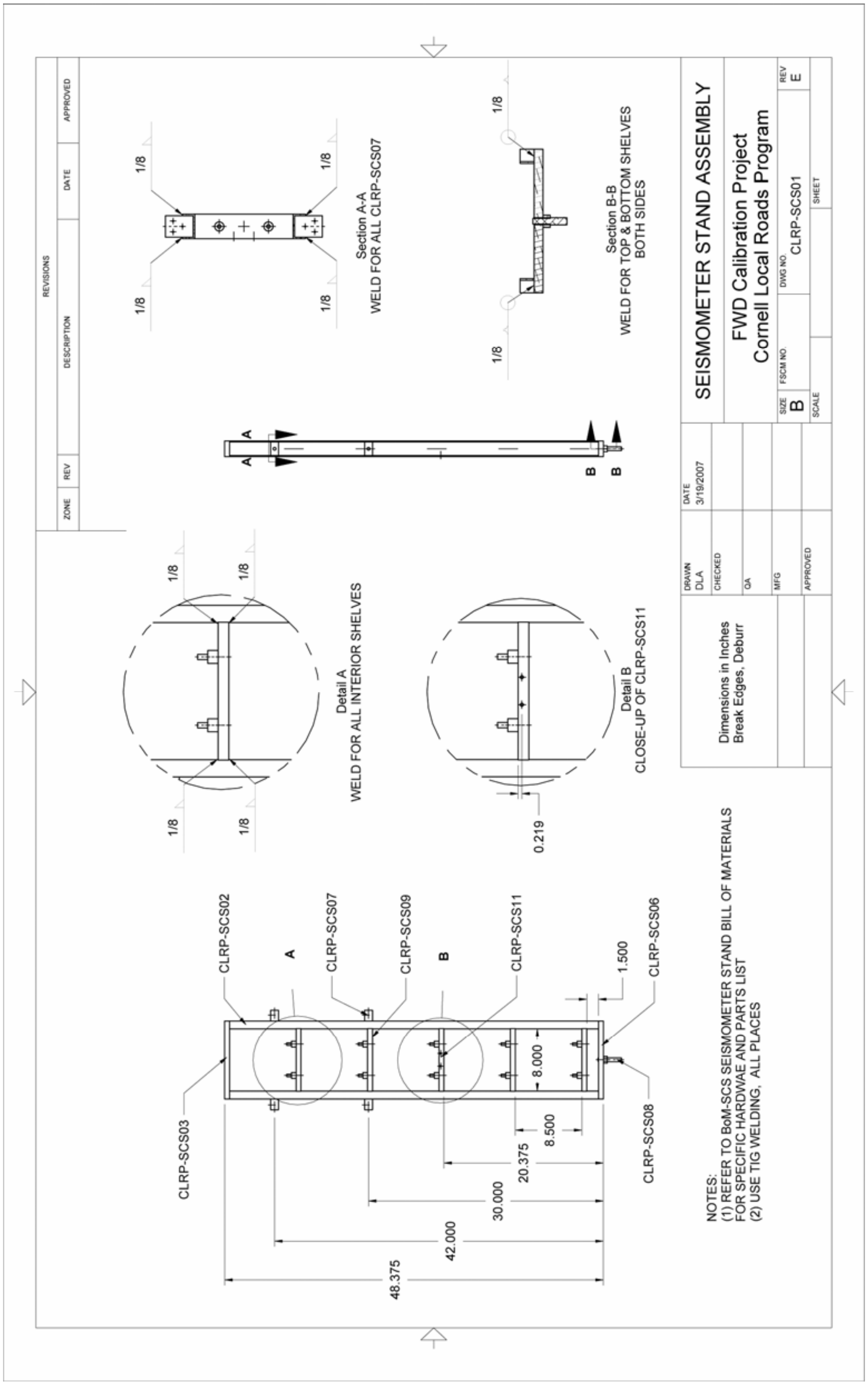

Figure 48. Drawing. CLRP-SCS01 Seismometer Stand Assembly.

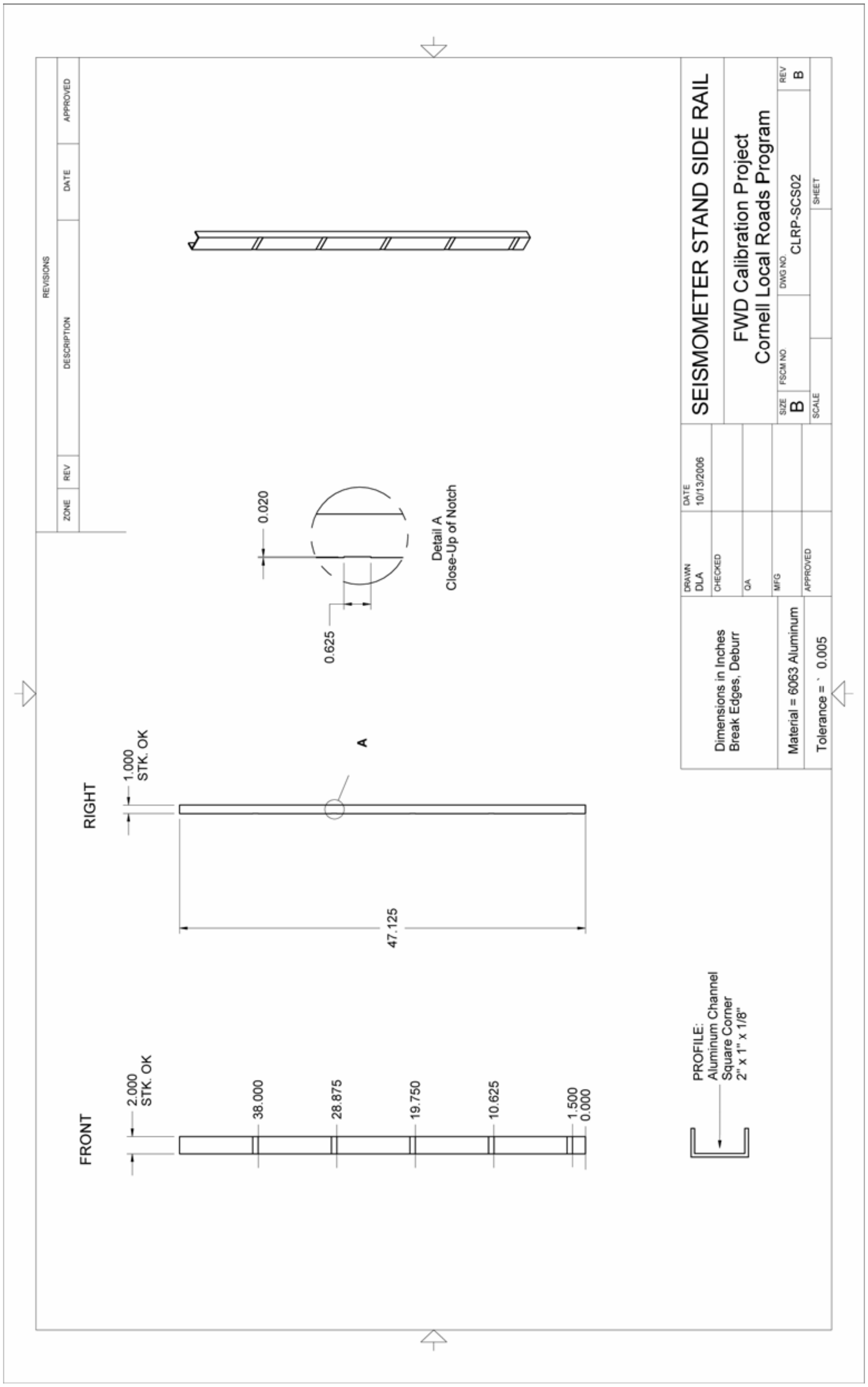

Figure 49. Drawing. CLRP-SCS02 Seismometer Stand Side Rail.

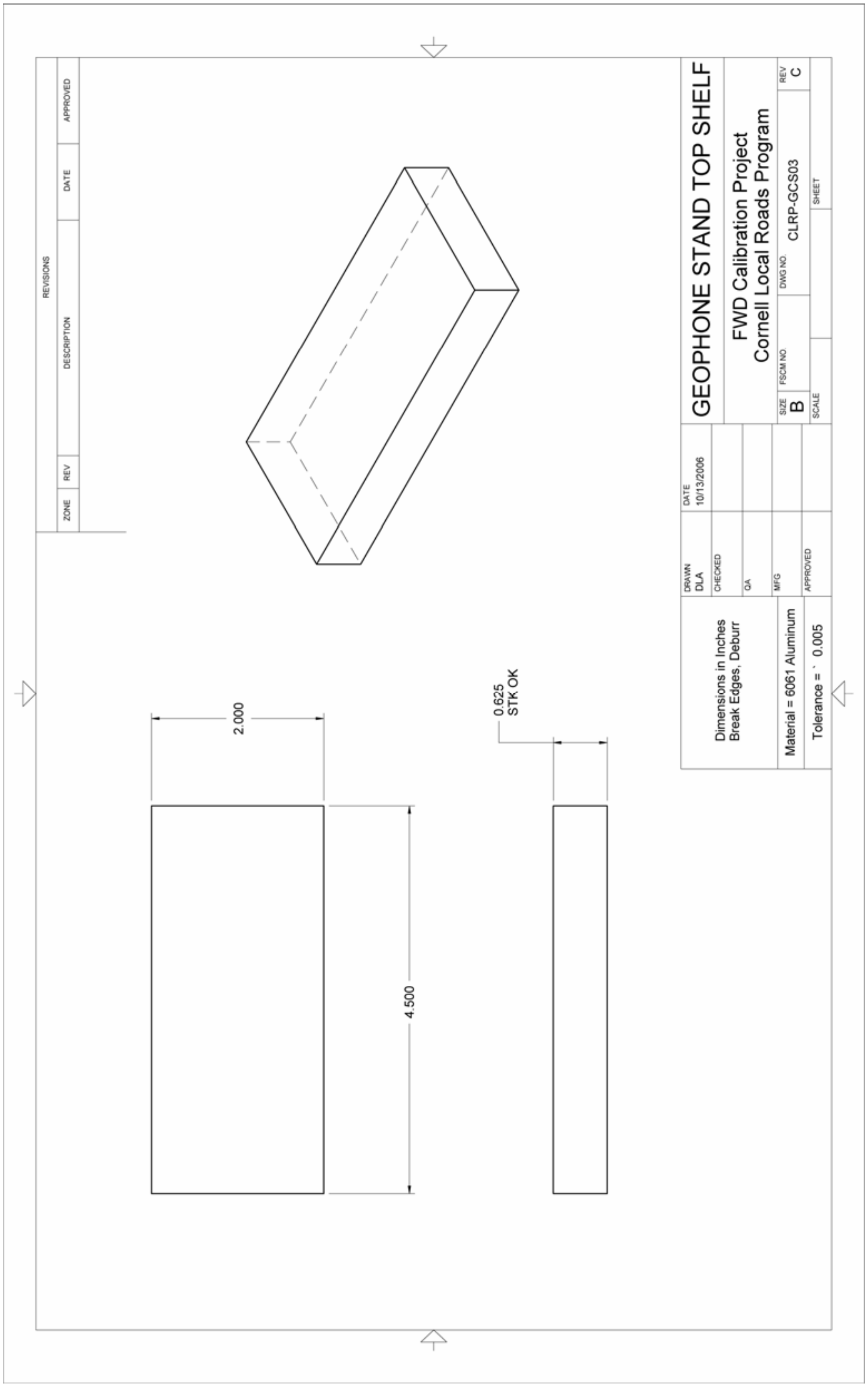

Figure 50. Drawing. CLRP-SCS03 Seismometer Stand Top Shelf.

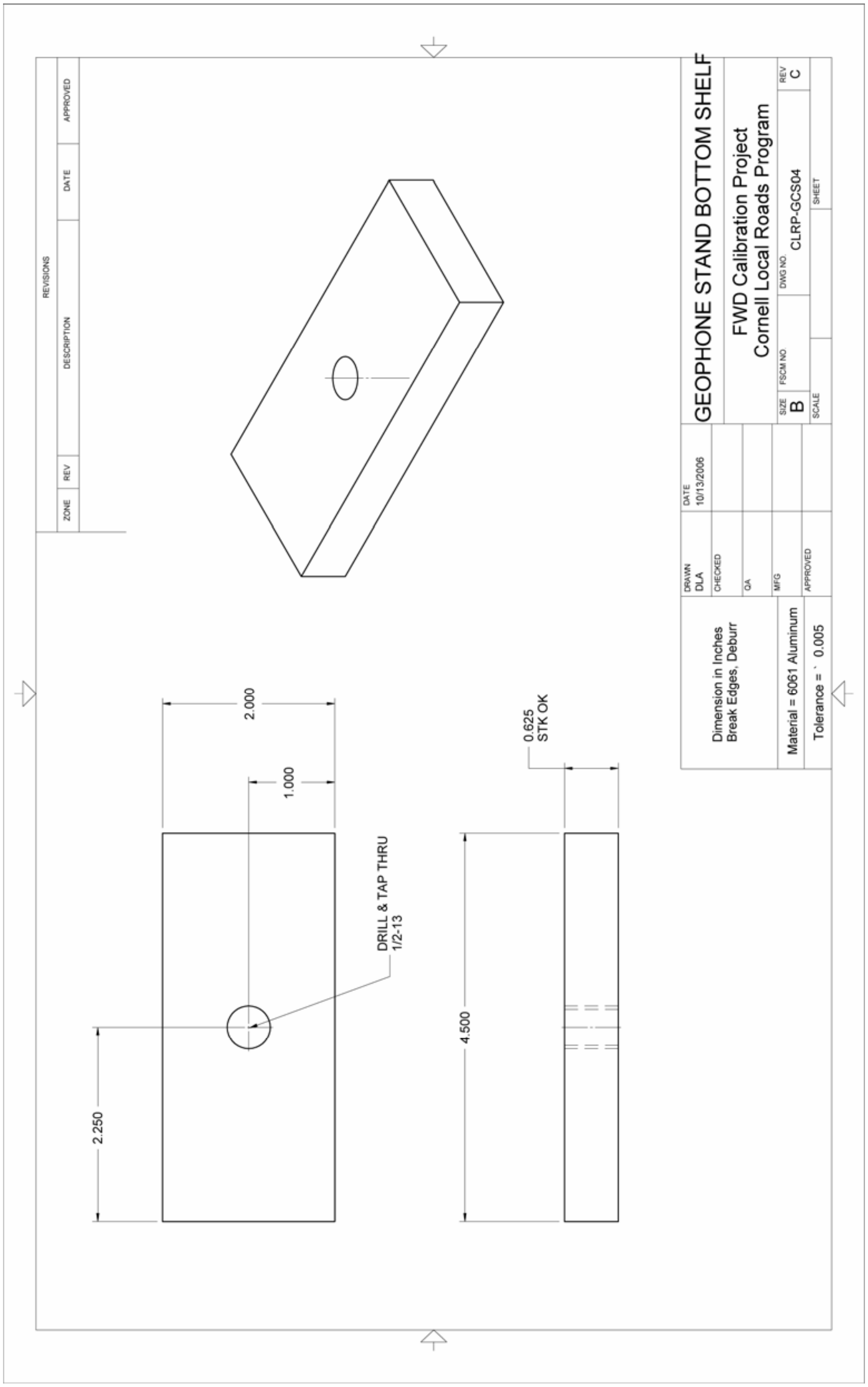

Figure 51. Drawing. CLRP-SCS04 Seismometer Stand Sensor Shelf.

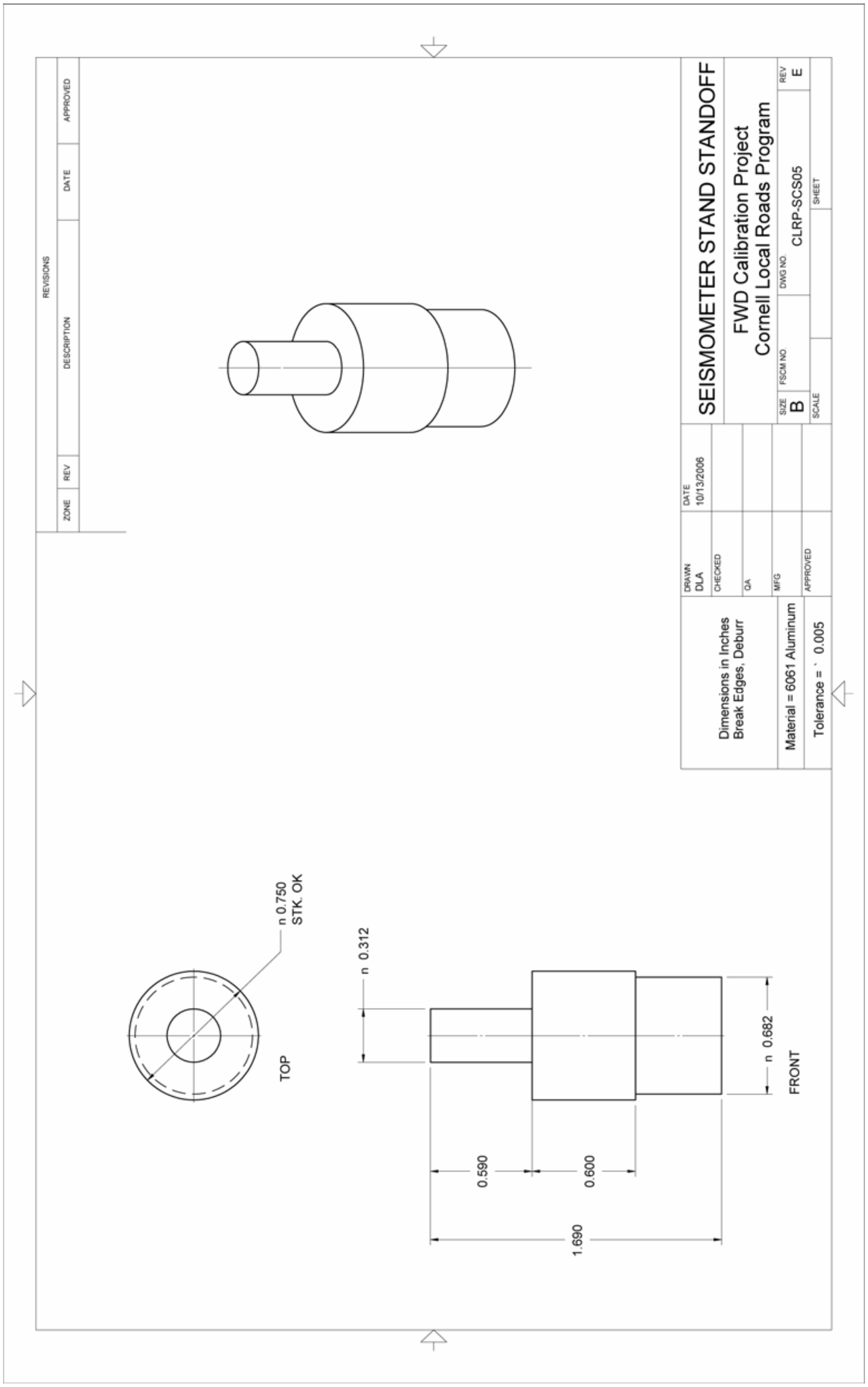

Figure 52. Drawing. CLRP-SCS05 Seismometer Stand Standoff.

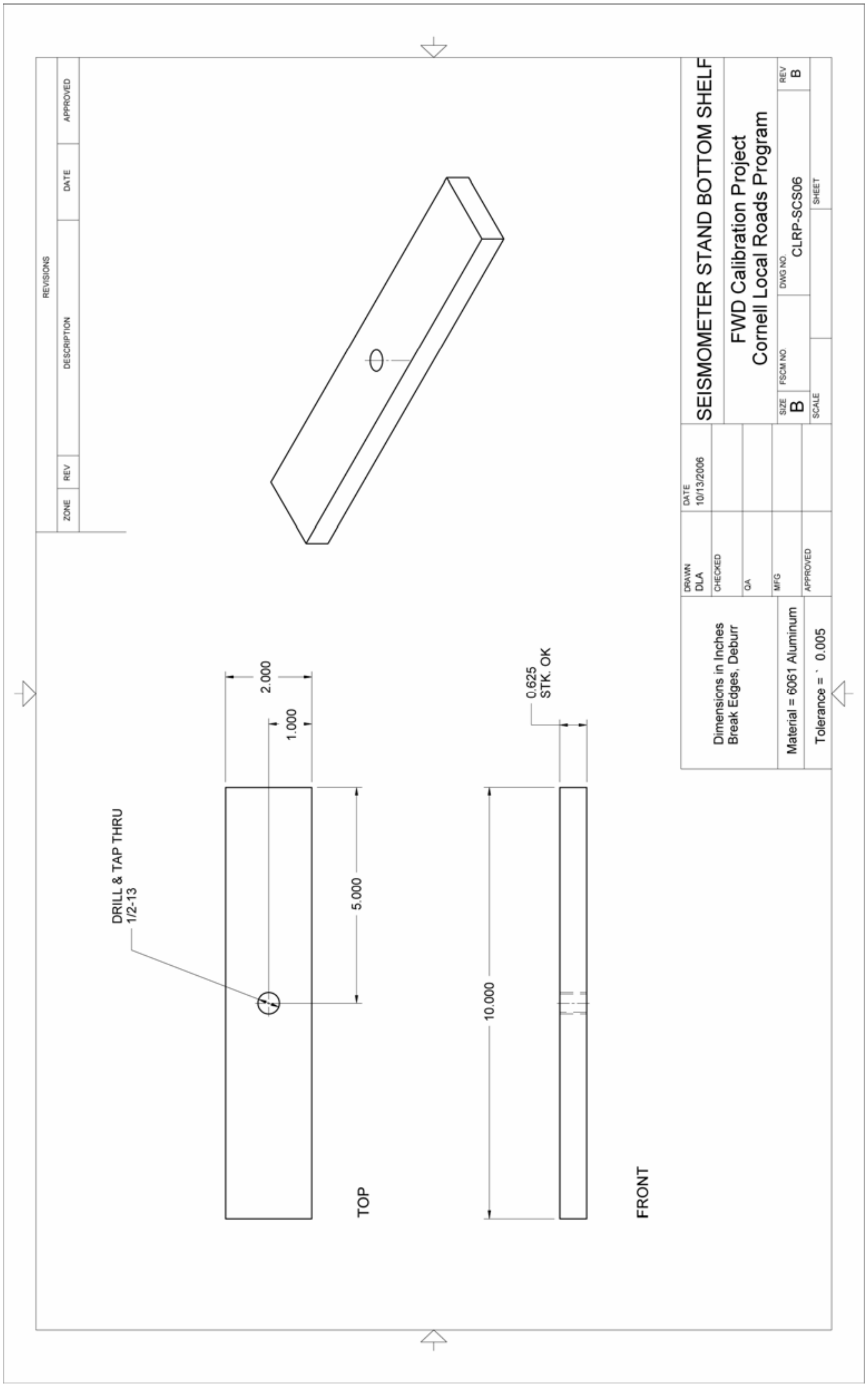

Figure 53. Drawing. CLRP-SCS06 Seismometer Stand Bottom Shelf.

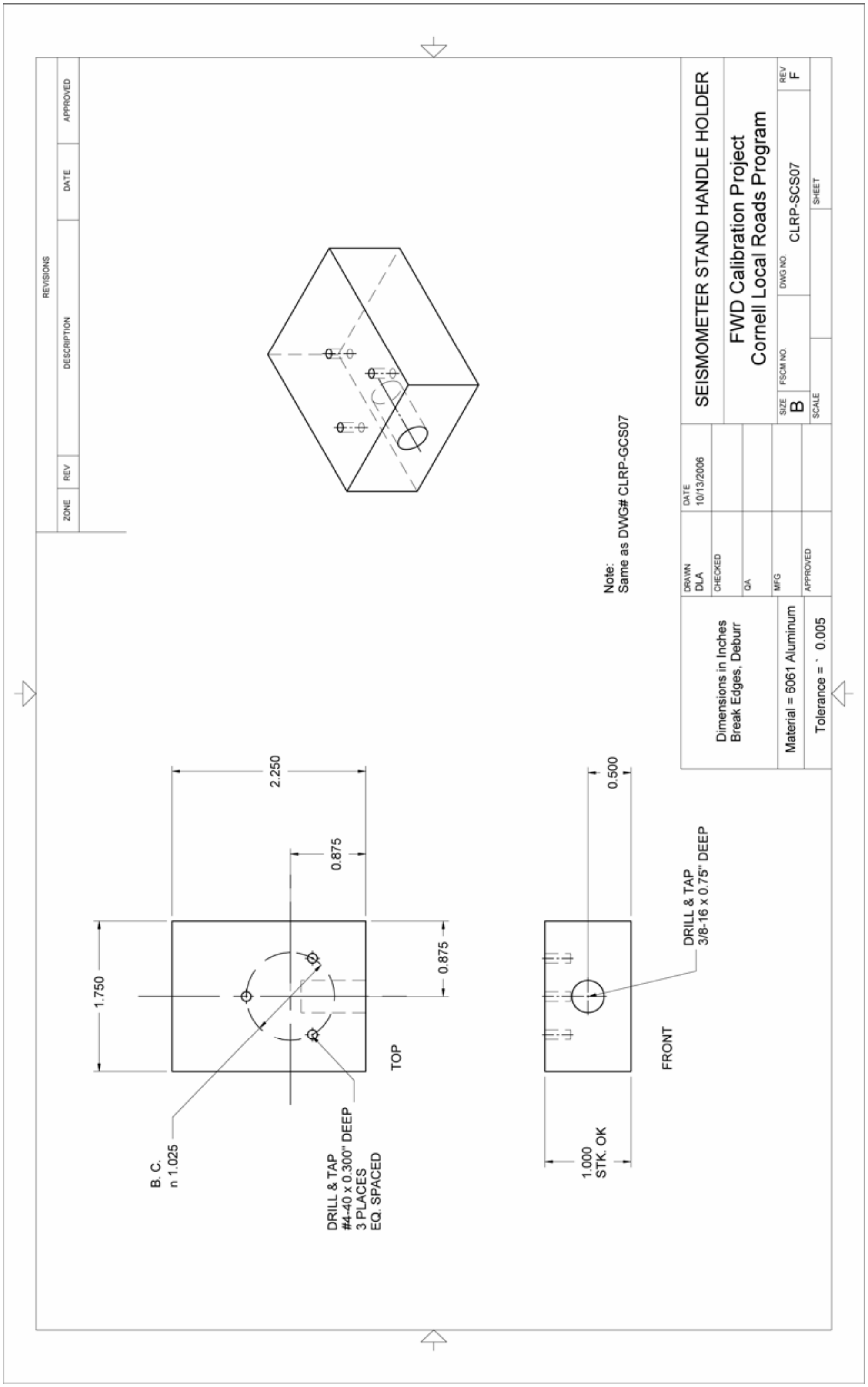

Figure 54. Drawing. CLRP-SCS07 Seismometer Stand Handle Holder.

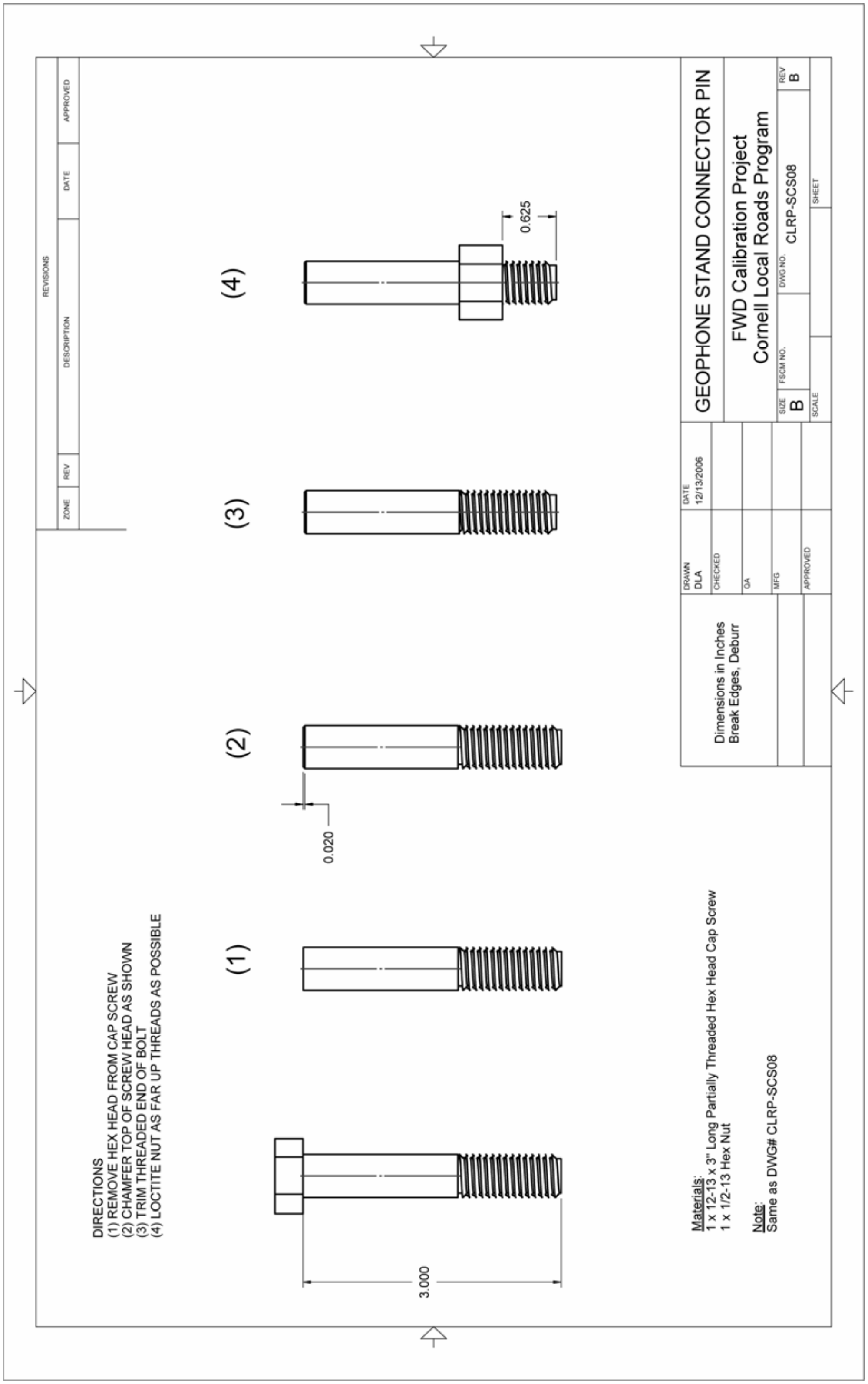

Figure 55. Drawing. CLRP-SCS08 Seismometer Stand Connector Pin.

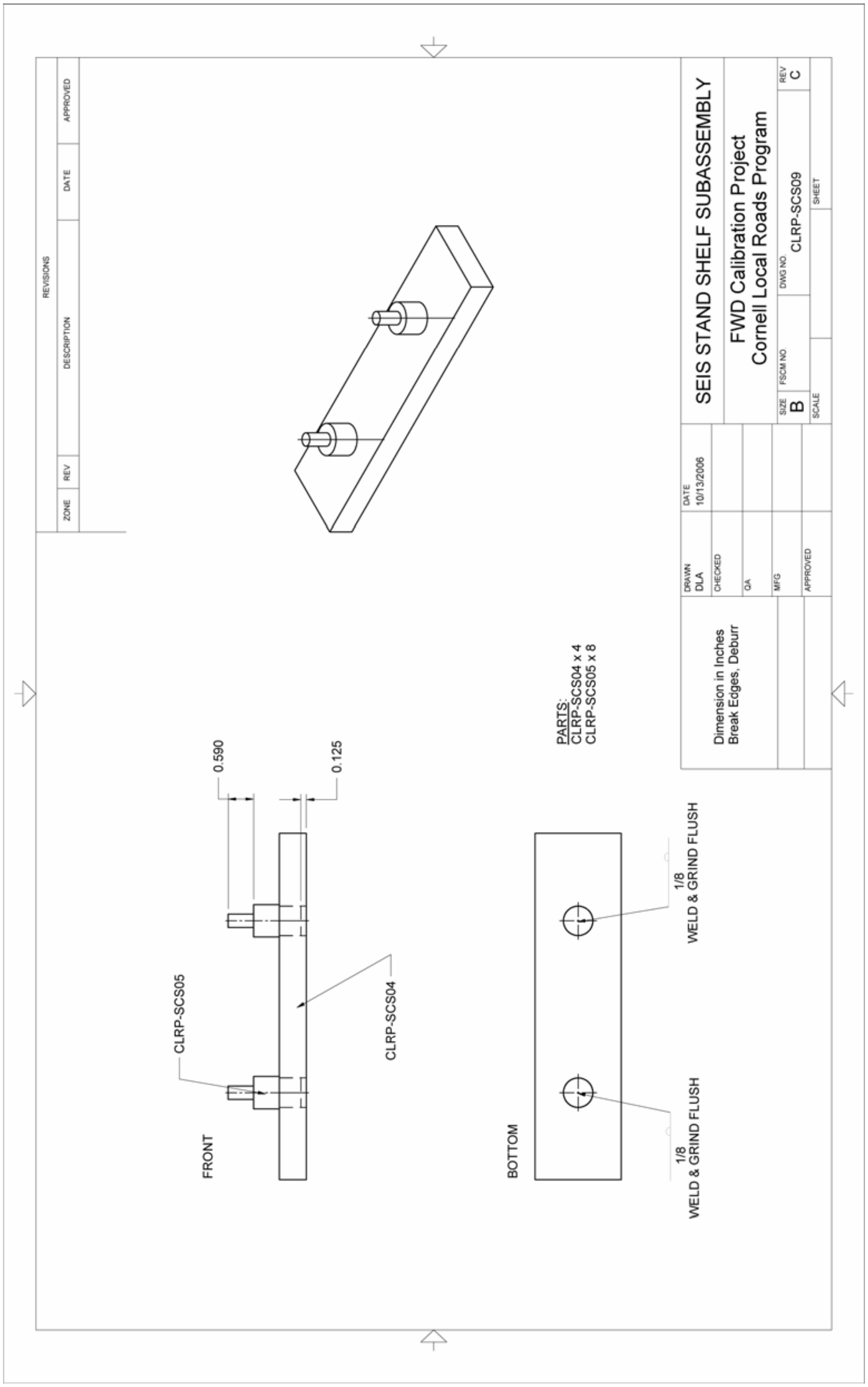

Figure 56. Drawing. CLRP-SCS09 Seismometer Stand Shelf Subassembly.

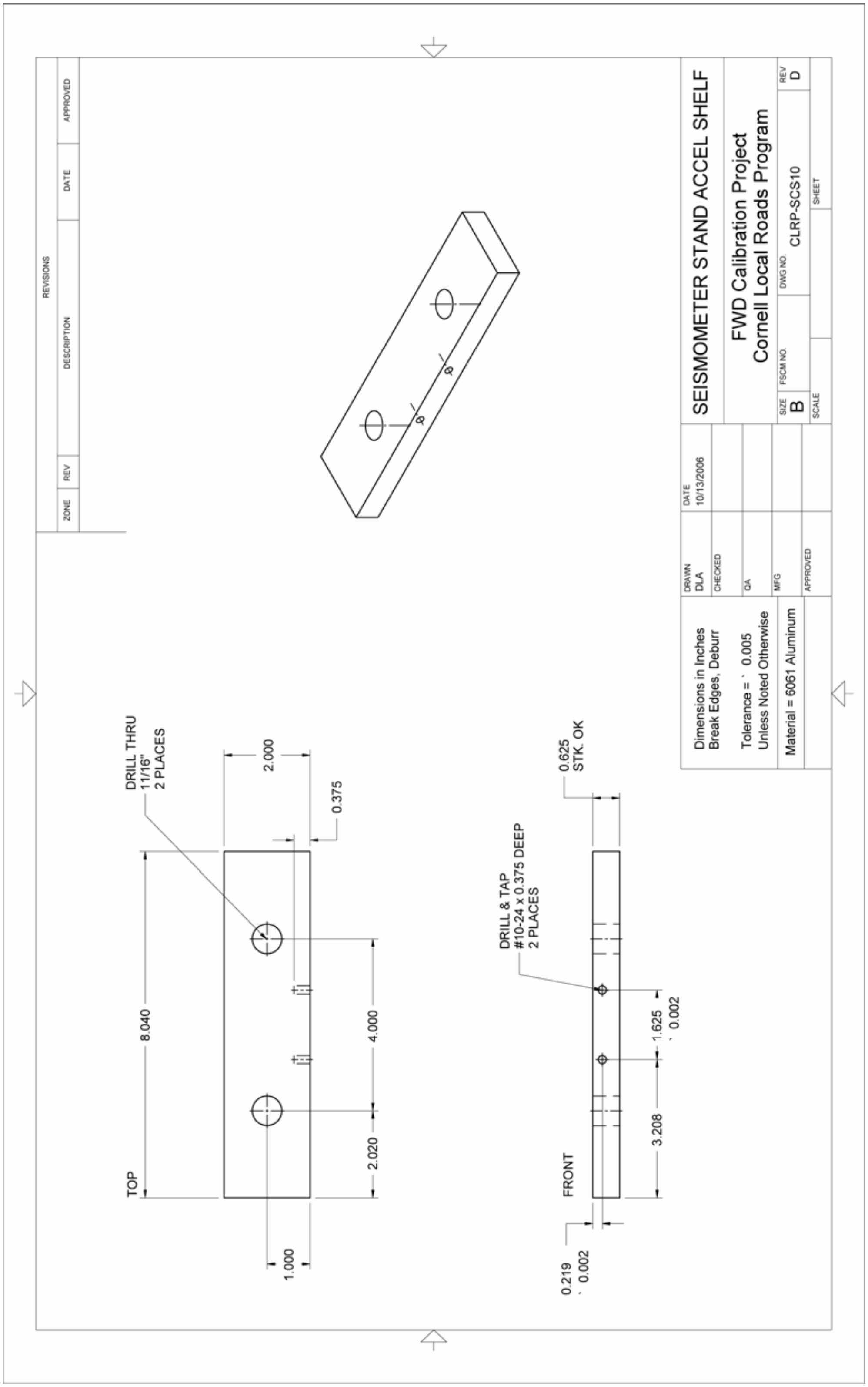

Figure 57. Drawing. CLRP-SCS10 Seismometer Stand Accelerometer Shelf.

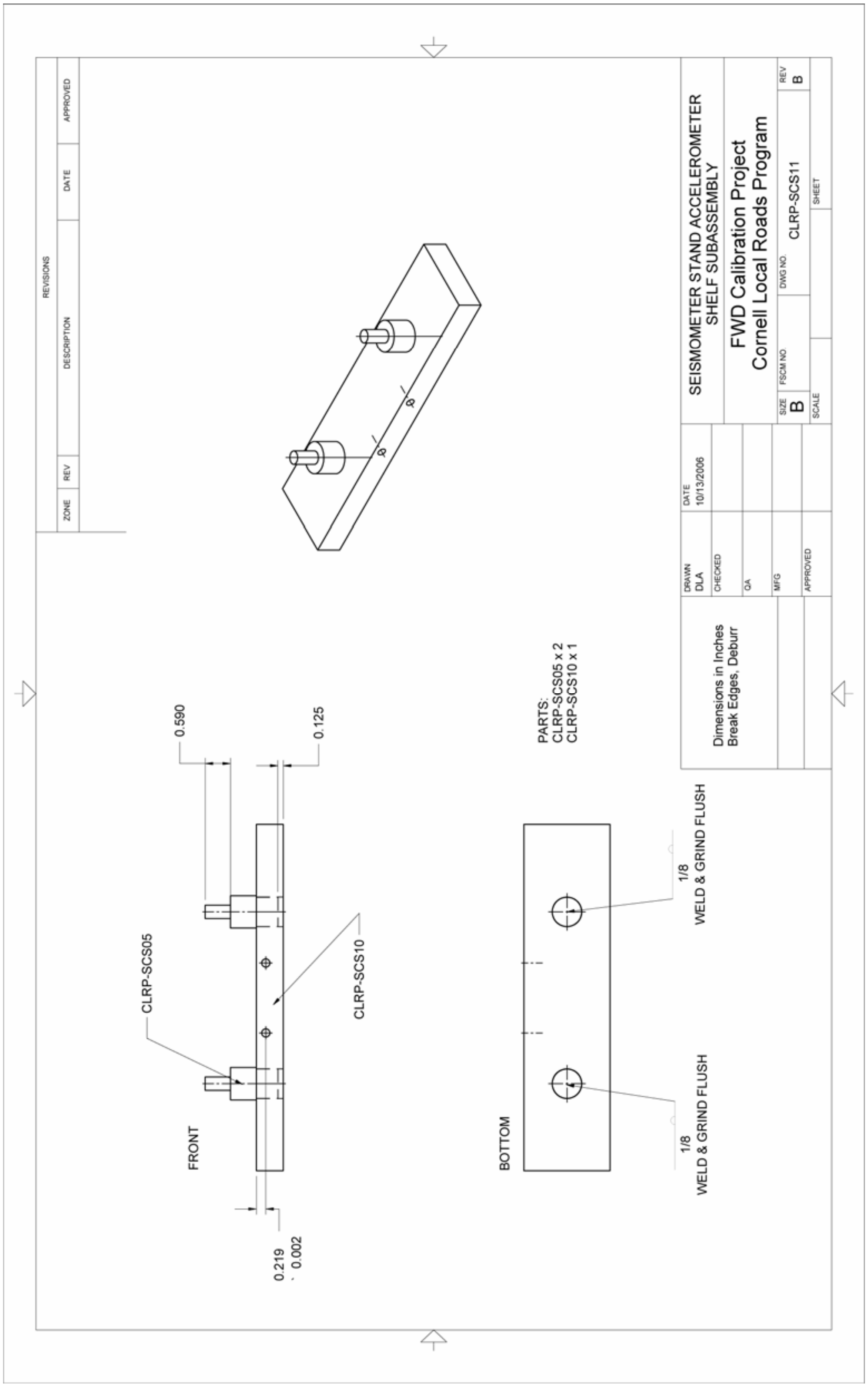

Figure 58. Drawing. CLRP-SCS11 Seismometer Stand Accelerometer Shelf Subassembly.

GEOPHONE ADAPTERS

BM-GA Geophone Adapters Bill of Materials

Table 28. Fabricated parts for use as geophone adapters.

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

Table 29. Hardware items required 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
91090A112	Flat Washer, Zinc-Plated Steel, 3/8" Screw Size, 13/32" Inside Diameter, 1" Outside Diameter, 0.043"- 0.063" 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

Table 30. 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 31. 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		$45.00	Price for all 10 adapters.

*Indicates the cost for the Cornell team.

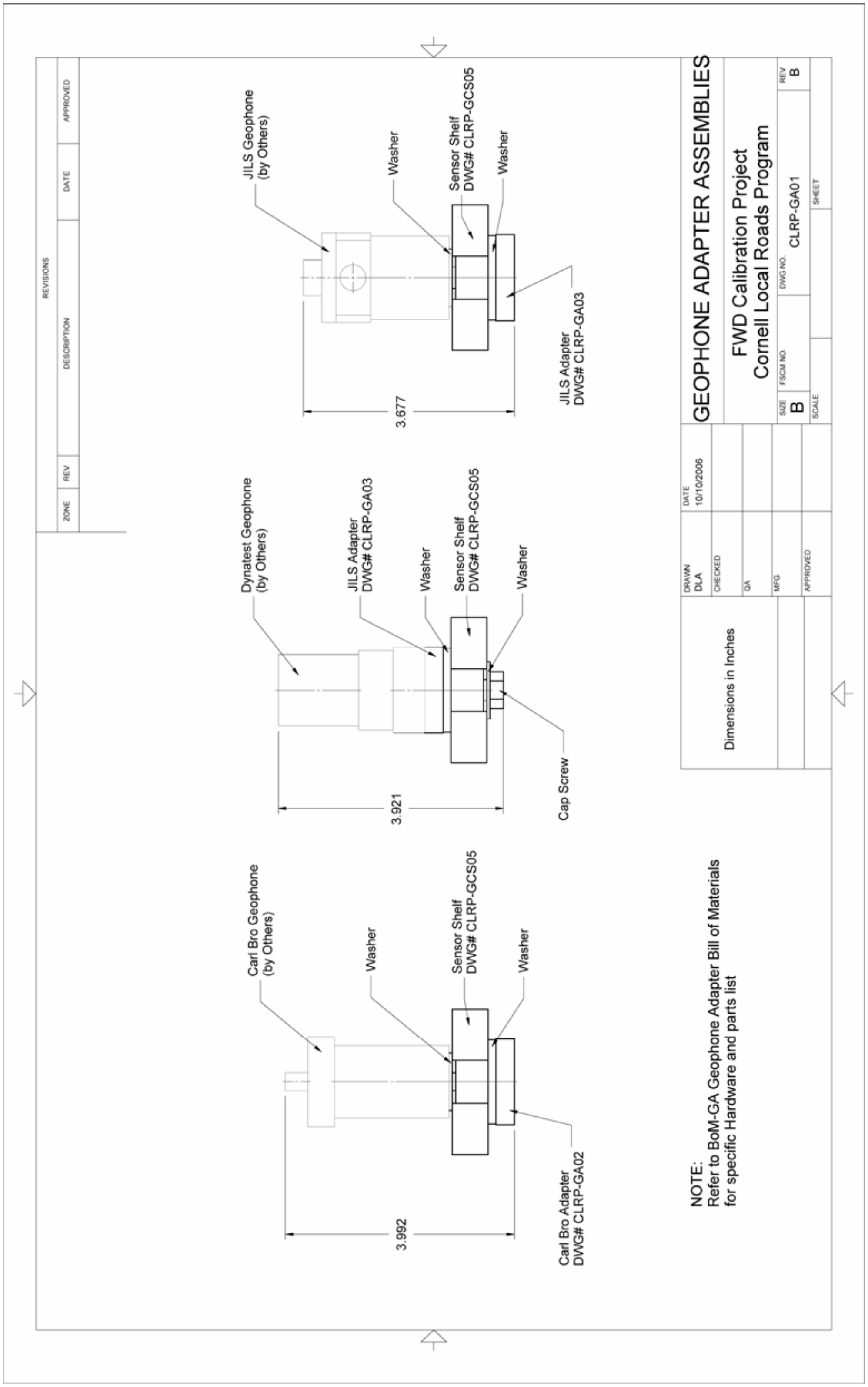

Figure 59. Drawing. CLRP-GA01 Geophone Adapter Assemblies.

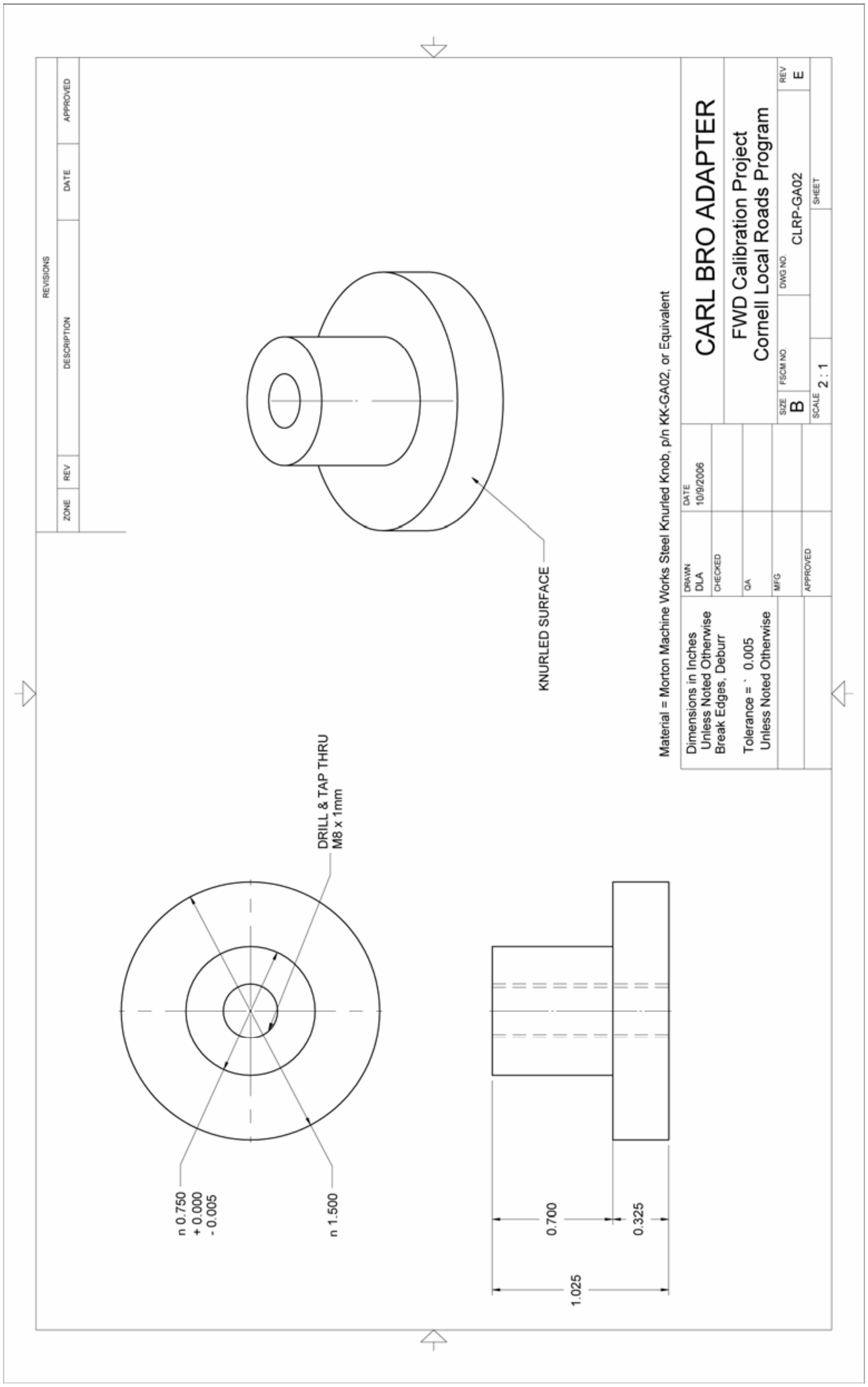

Figure 60. Drawing. CLRP-GA02 Carl Bro Adapter.

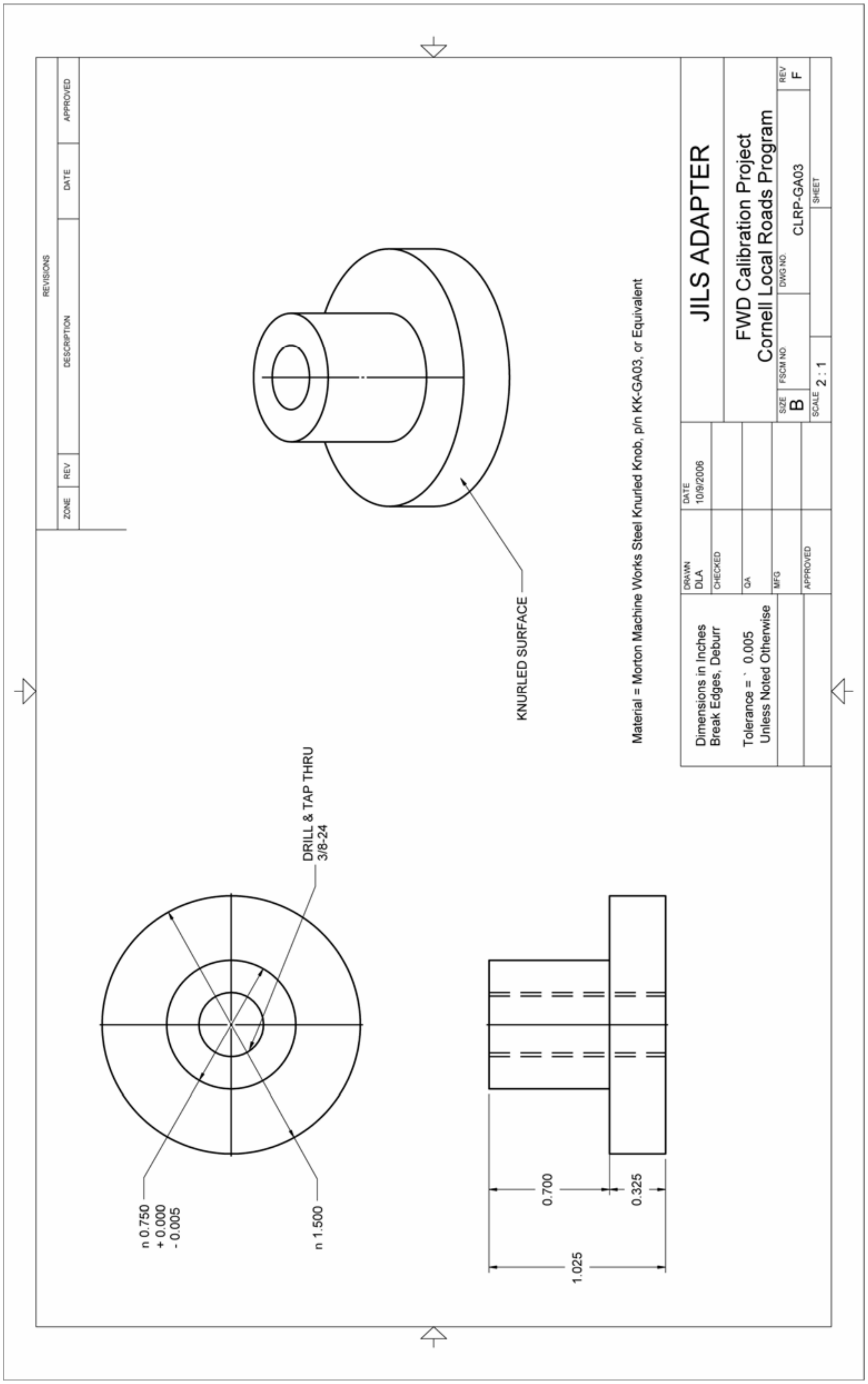

Figure 61. Drawing. CLRP-GA03 JILS Adapter.

DATA ACQUISITION

BM-DAQ Data Acquisition Bill of Materials

Table 32. Cable diagrams required for data acquisition.

Dwg. Number	Description	Quantity
CLRP-DAQ01	Vishay to KUSB DAQ Cable	1
CLRP-DAQ02	Vishay to Load Cell Cable	1
CLRP-DAQ03	Accelerometer Signal Cable	1
CLRP-DAQ04	Pushbutton to KUSB DAQ Cable	1

Table 33. Equipment and hardware items required for data acquisition.

Vendor Part Number	Item	Vendor	Quantity
Model 2310	Vishay 2310 Signal Conditioner	Vishay Micro-Measurements	1
KUSB-3108	Keithley 16-bit USB Data Acquisition Board	Keithley	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
278-0232	Enclosure, Black Plastic	Allied Electronics	1

Vendor Part Number	Item	Vendor	Quantity
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	
	USB Memory Drive, minimum 256 MB	Local Computer Supply	1

Table 34. 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

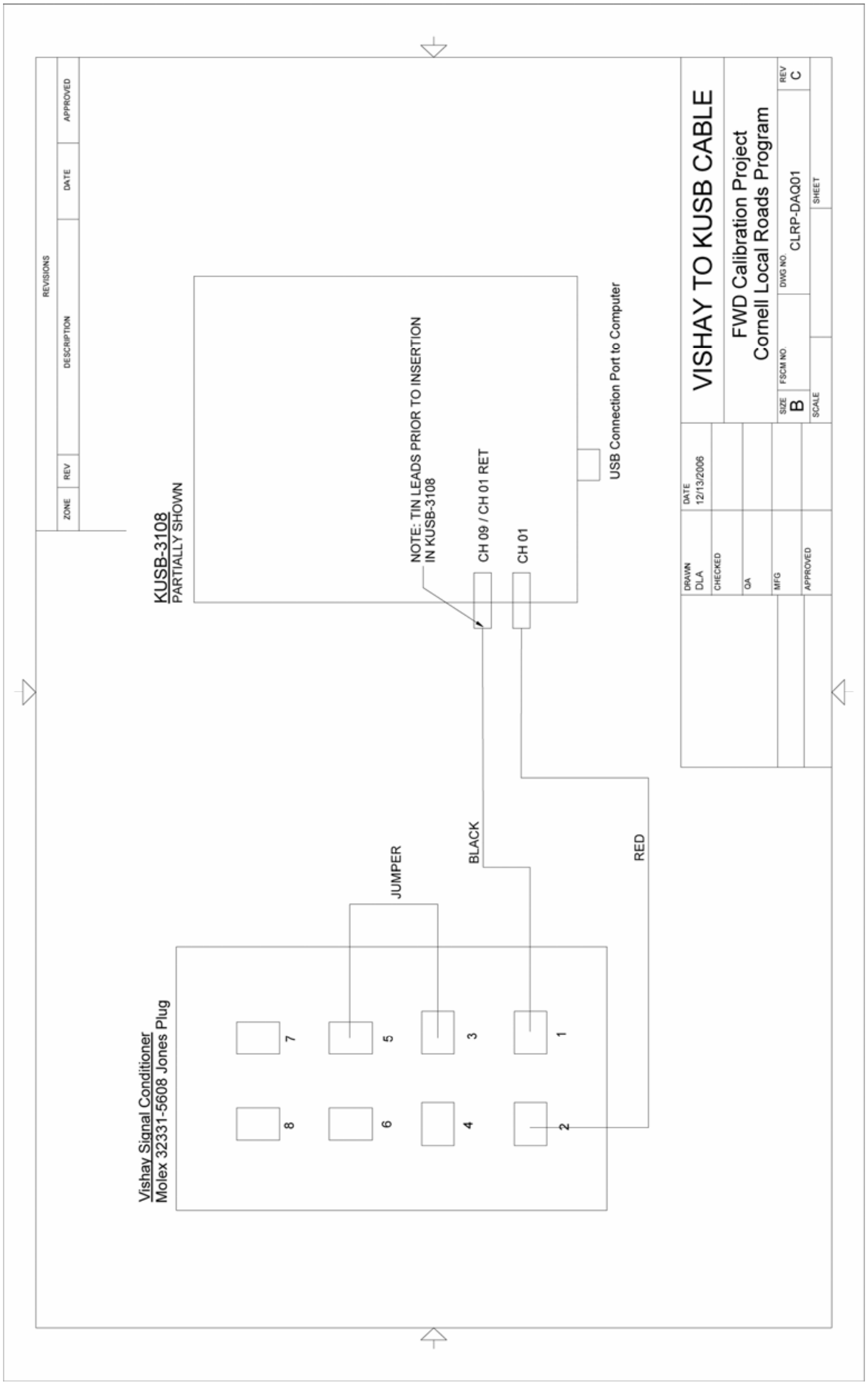

Figure 62. Drawing. CLRP-DAQ01 Vishay to KUSB Cable.

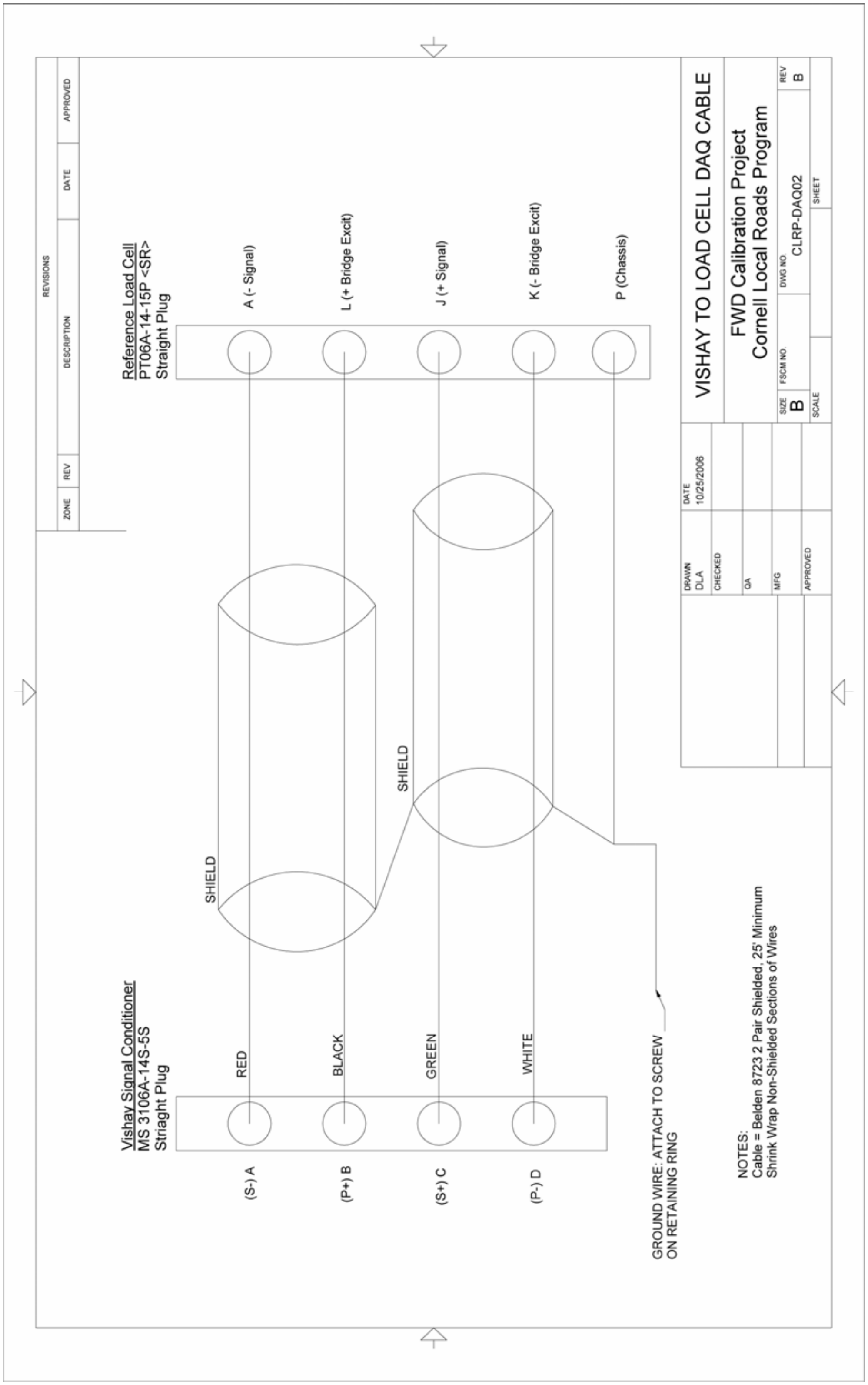

Figure 63. Drawing. CLRP-DAQ02 Vishay to Load Cell DAQ Cable.

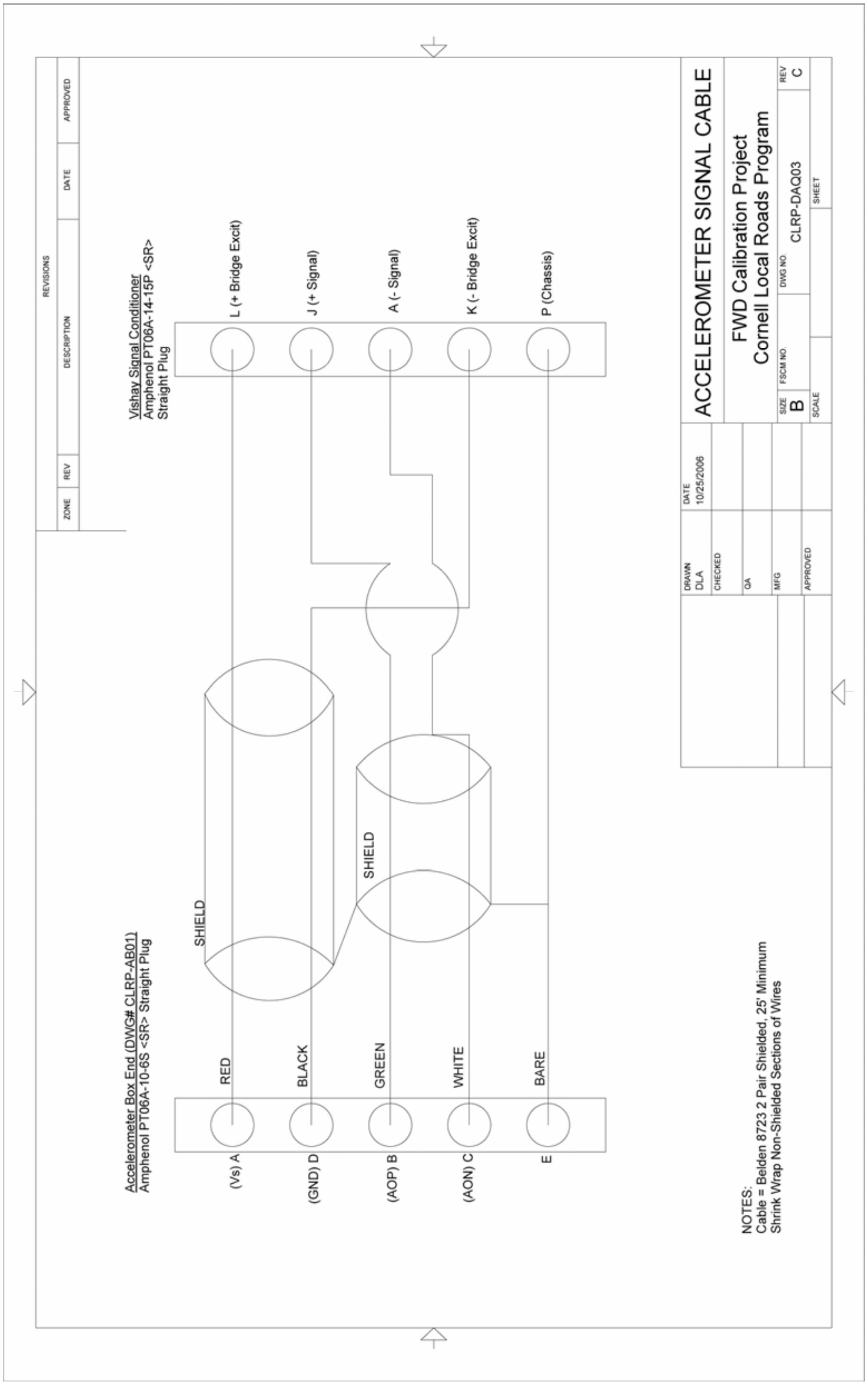

Figure 64. Drawing. CLRP-DAQ03 Accelerometer Signal Cable.

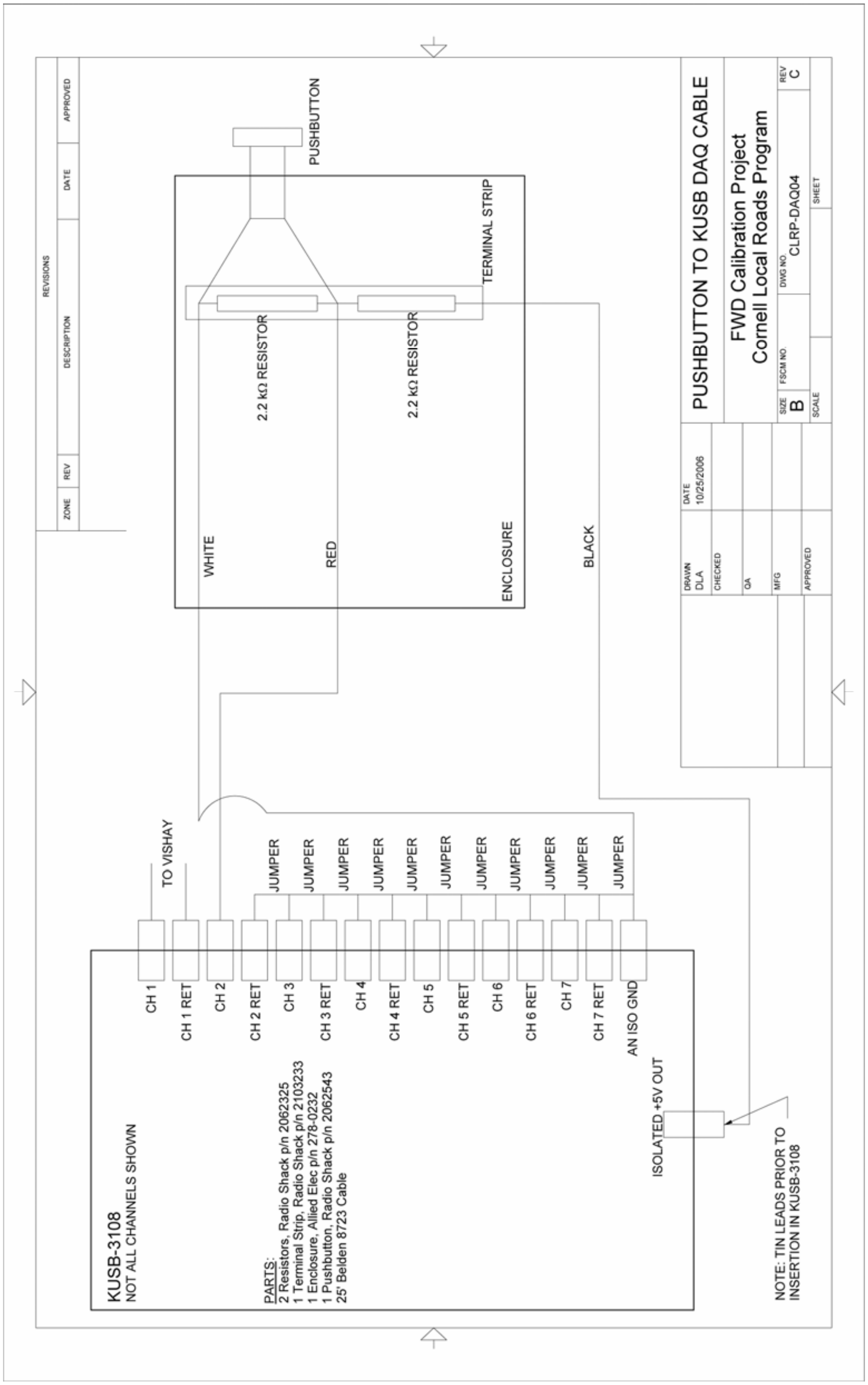

Figure 65. Drawing. CLRP-DAQ04 Pushbutton to KUSB DAQ Cable.

APPENDIX III. 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
- 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)

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

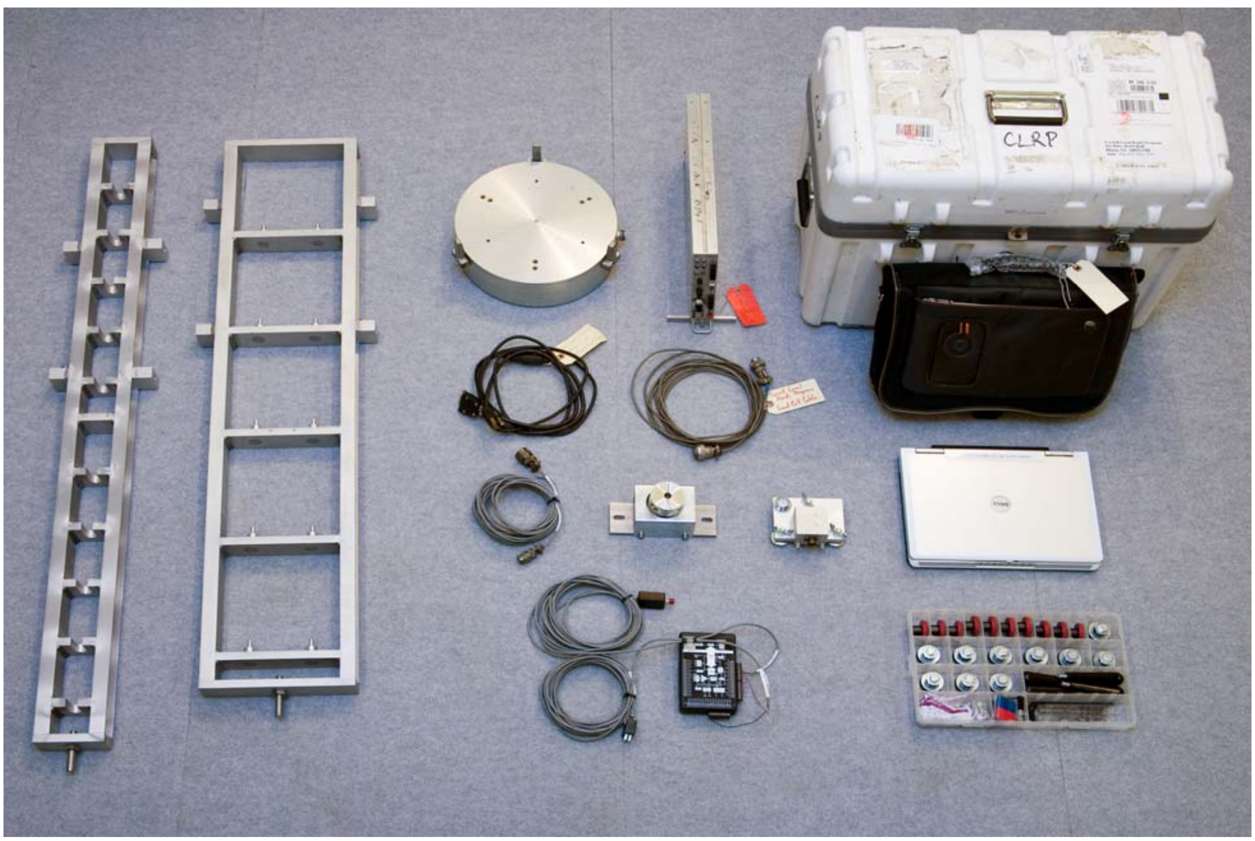

Figure 66. Photo. Calibration system components.

FACILITIES

Calibration center facilities require the following characteristics:

- Easy access for the FWD trailer and the tow vehicle.
- A large, level floor that can accommodate both the FWD trailer and the tow vehicle indoors.
- A stable indoor temperature between 50 °F and 100 °F (10 to 38 C).
- 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):

- 12 feet by 15 feet (4.0 by 4.5 meters), with an 8-foot (2.5-meter) wide (5 foot (1.75 meter) 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 (1/16 inch 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 16,000 pounds (71 kN).

LOAD CELL

Parts and Tools

Table 35. 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-lbs

Figure 67. Photo. SHRP reference load cell.

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 completed, 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.

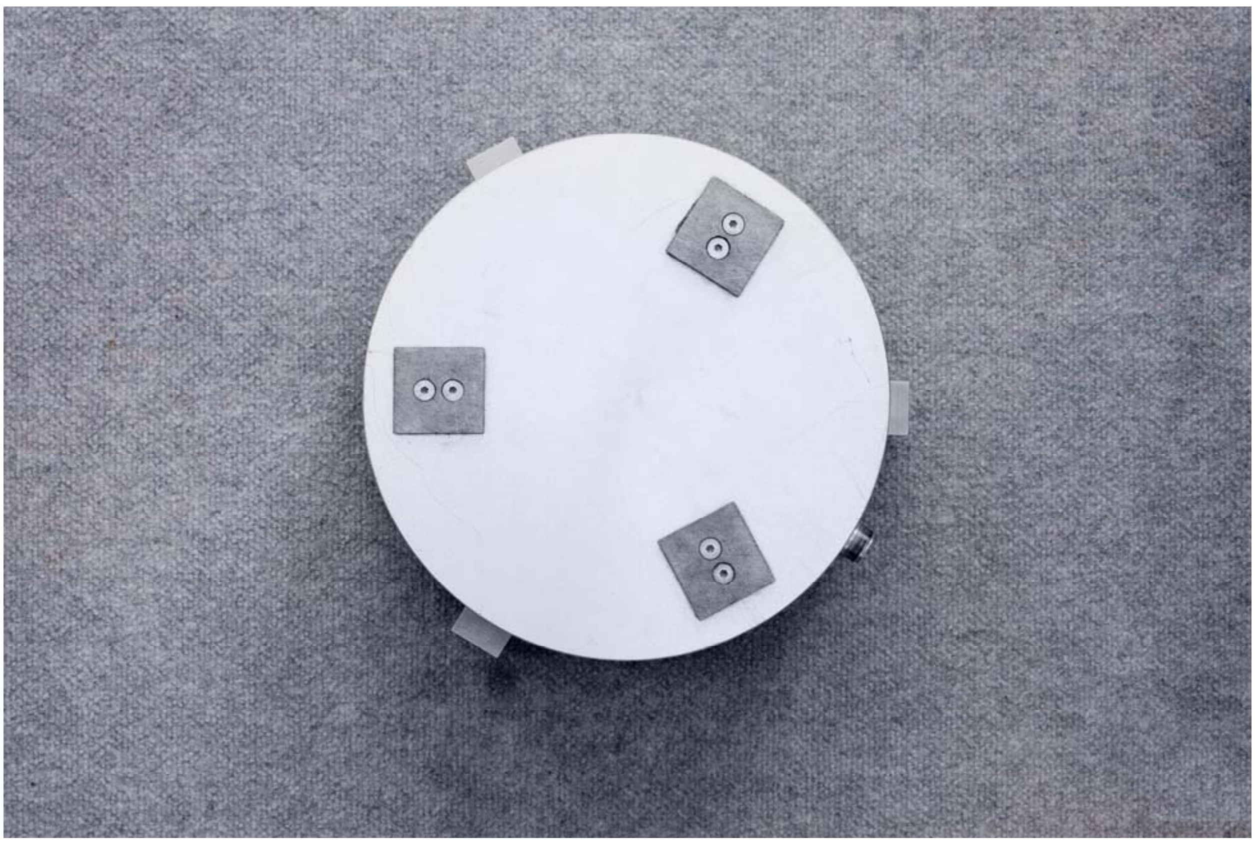

Figure 68. Photo. Bottom view of the reference load cell.

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 a t 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 69. 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 36. Parts and equipment for concrete anchor installation.

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 70. Photo. Concrete anchor.

Installation

5. Determine the appropriate location for the ball joint anchor on the test pad. The FWD needs to impart a deflection of 400 - 600 microns where the ball joint will be located at a 16,000 lbf (71 kN) load.

6. 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.

7. 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.

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

9. Clean the debris from holes.

10. 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.

11. 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 71. Photo. Concrete anchor installation, steps 3, 6, and 7.

BALL JOINT ANCHOR

Parts and Tools

Table 37. 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	Loctite #242 Threadlocker	1	
B10	5 mm Hex Wrench	1	
B11	6 mm Hex Wrench	1	
B12	Dow Corning Molykote G-4500 Alum Thickened Grease, 14.1-oz, Nlgi #2		McMaster-Carr p/n 4328T24

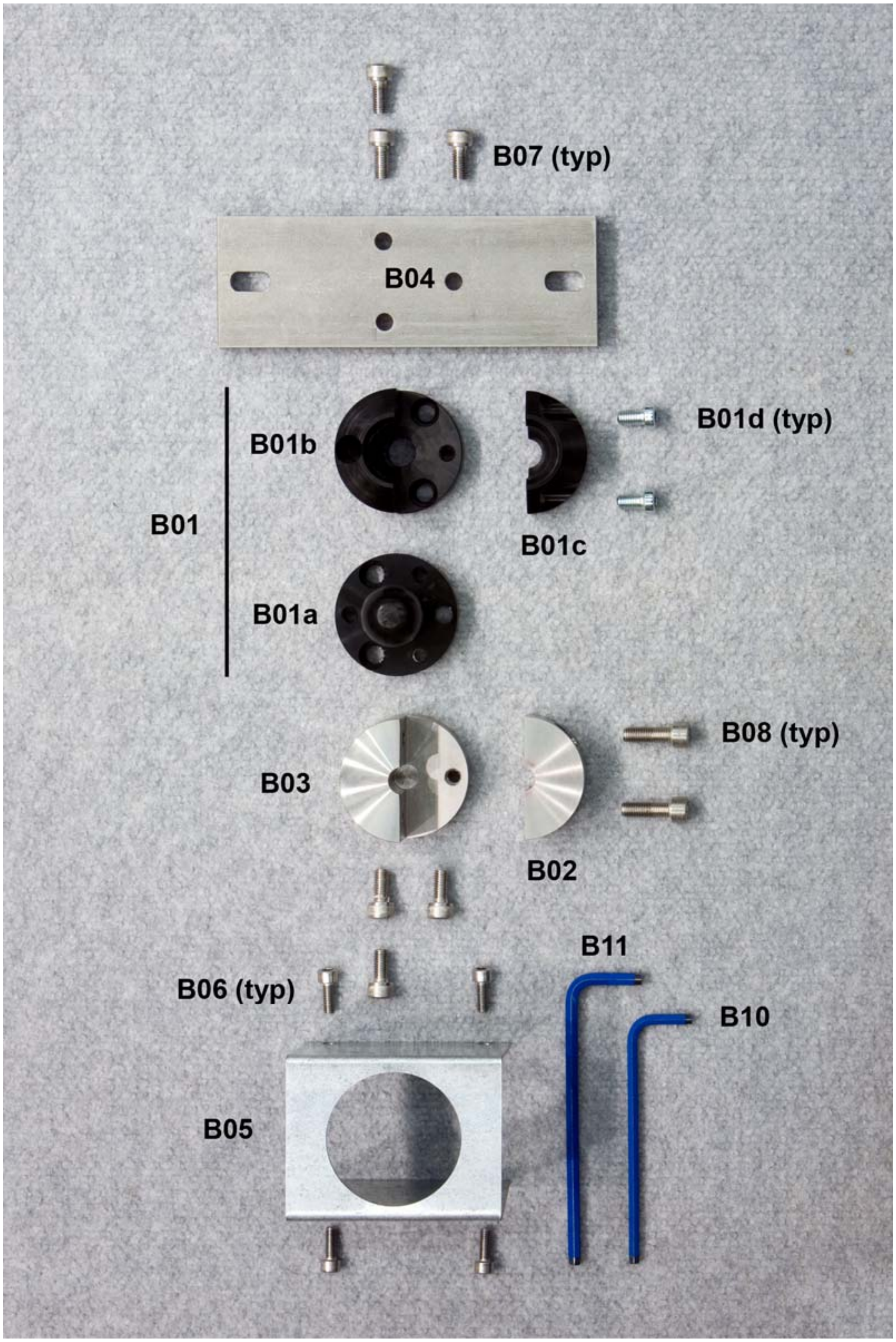

Figure 72. Photo. Parts and tools for ball joint assembly.

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 Loctite to the two screws.

12. 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.

13. Using Loctite 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.

14. Reassemble the ball joint (B01). Note: Do not apply Loctite when installing the screws (B01d).

15. Attach the base bar (B04) to the completed ball joint assembly with Loctite (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 73**.**

16. 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).

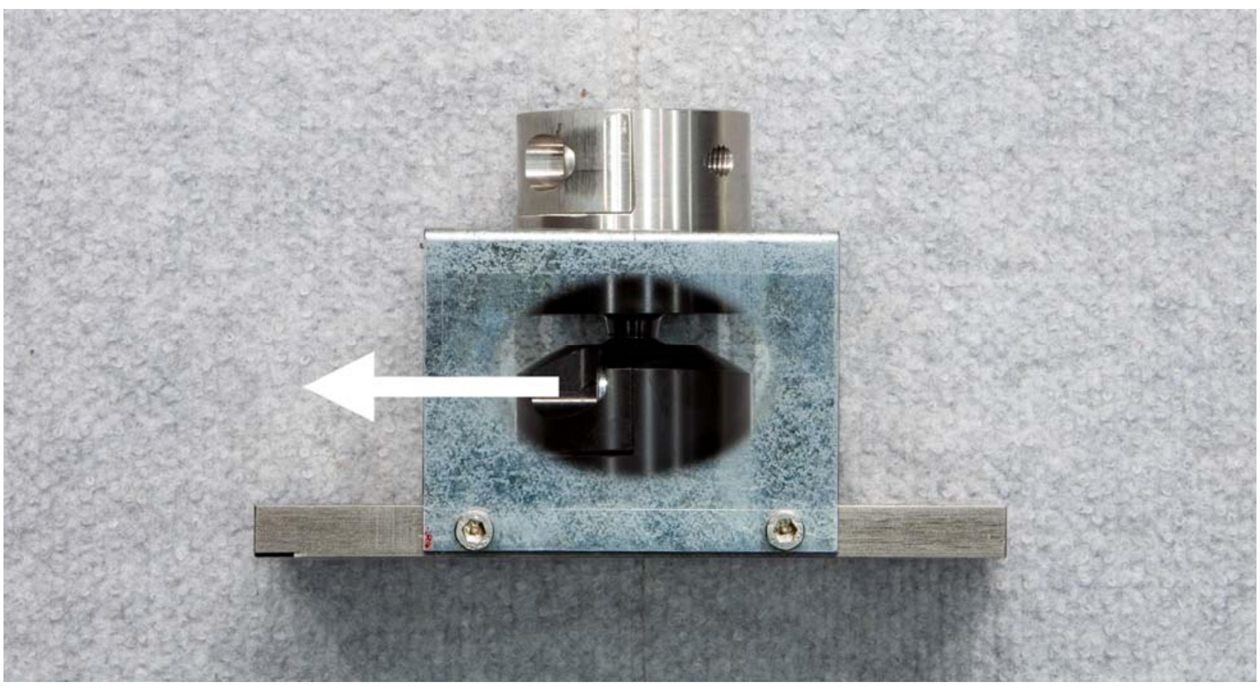

Figure 73. Photo. Proper alignment of ball joint screws.

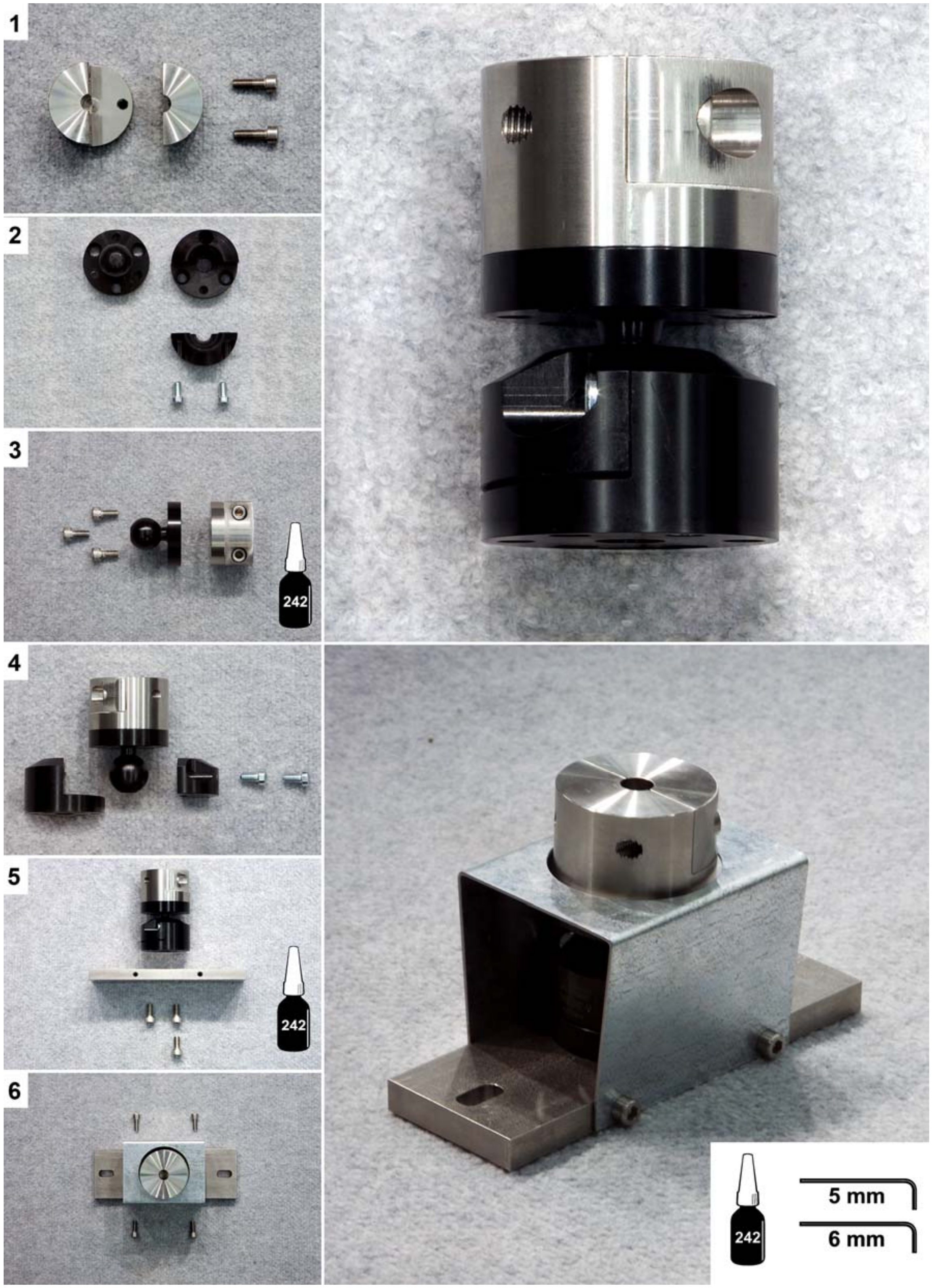

Figure 74. Photo. Assembly of the ball joint anchor.

ACCELEROMETER BOX

Parts and Tools

Table 38. 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	Loctite #242 Threadlocker	1	

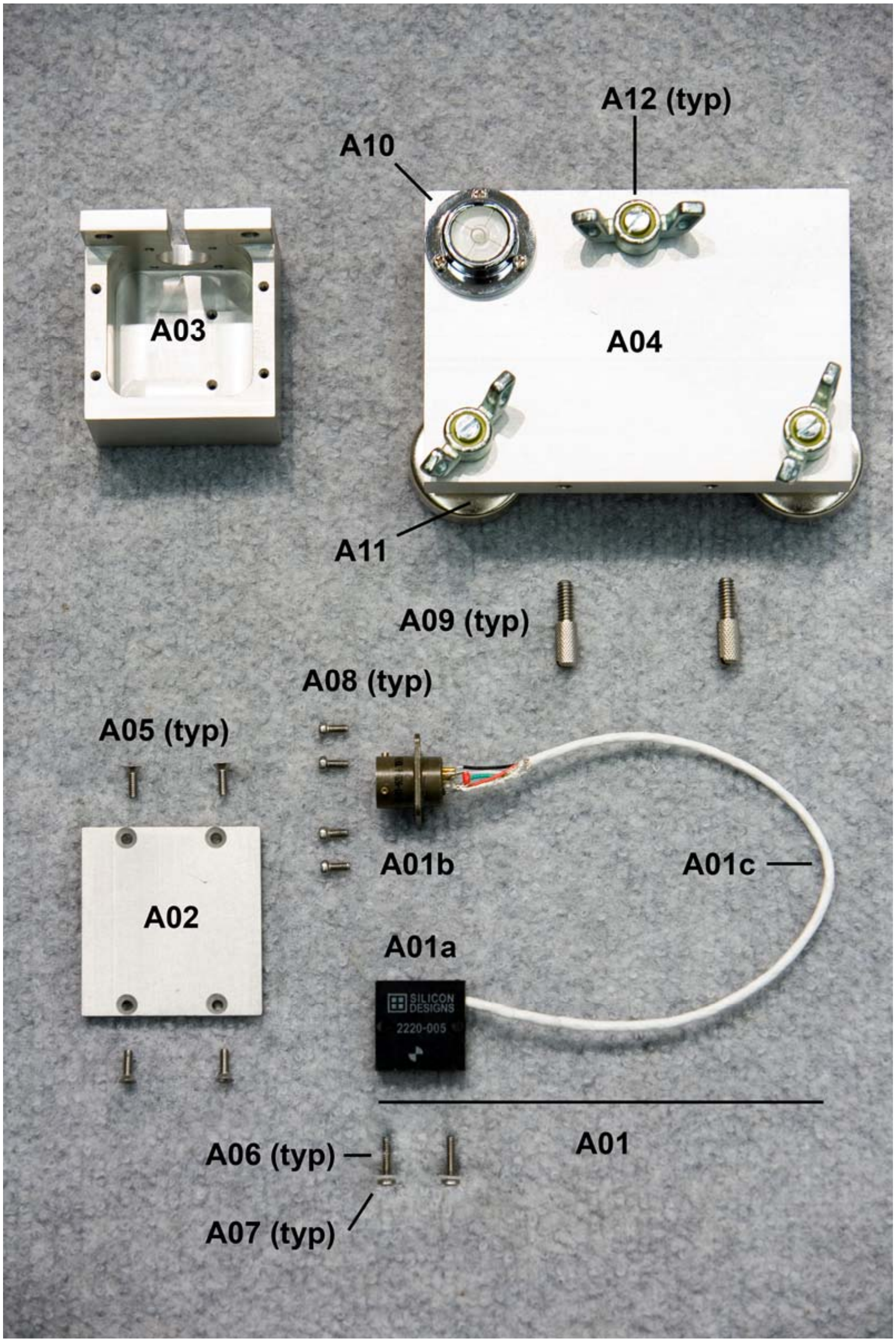

Figure 75. Photo. Parts for accelerometer box assembly.

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 75. 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 Loctite #242 (A14).

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 Loctite #242 (A14). The final assembly is shown in Figure 76.

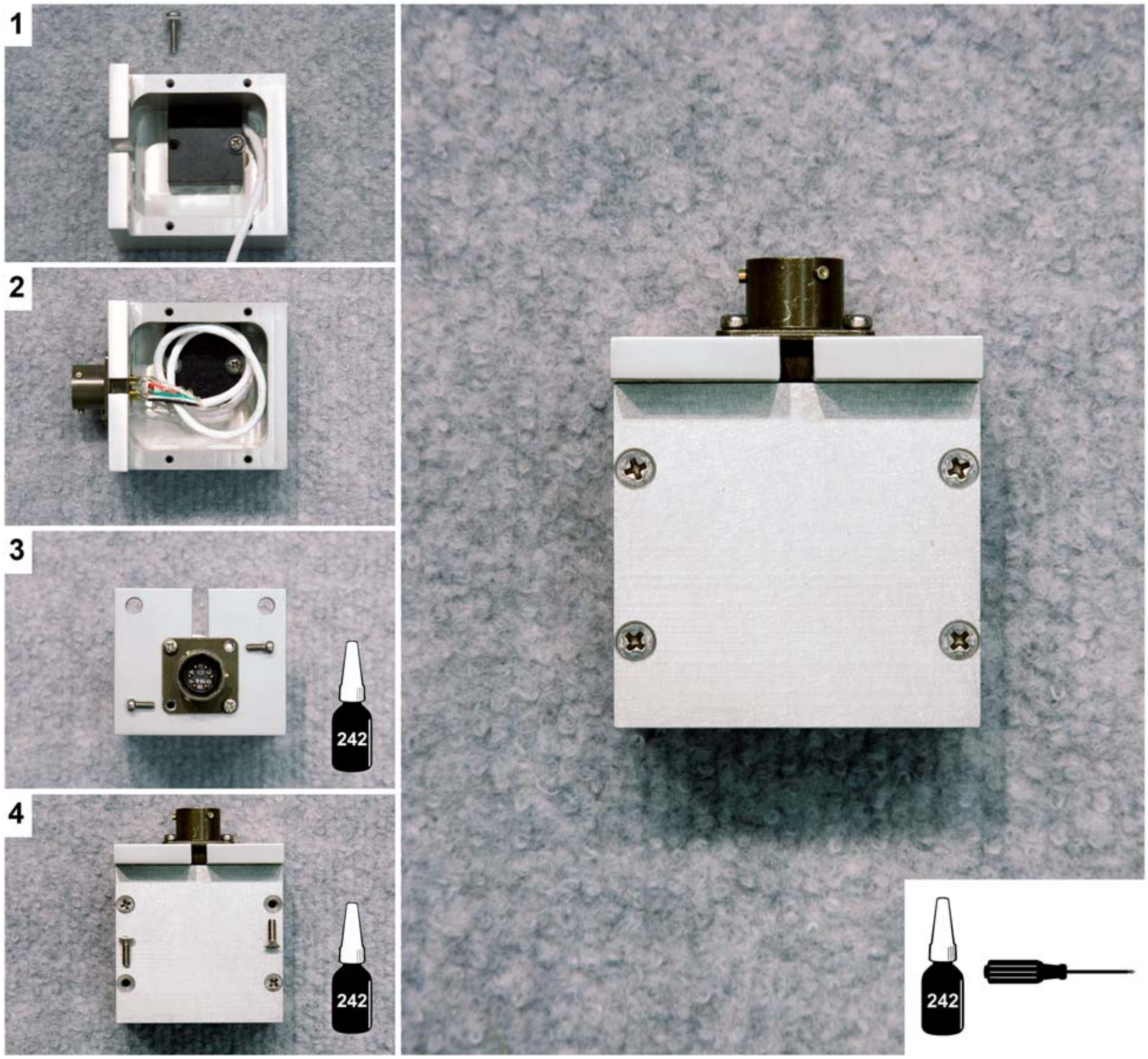

Figure 76. Photo. Accelerometer box assembly.

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 77.

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.

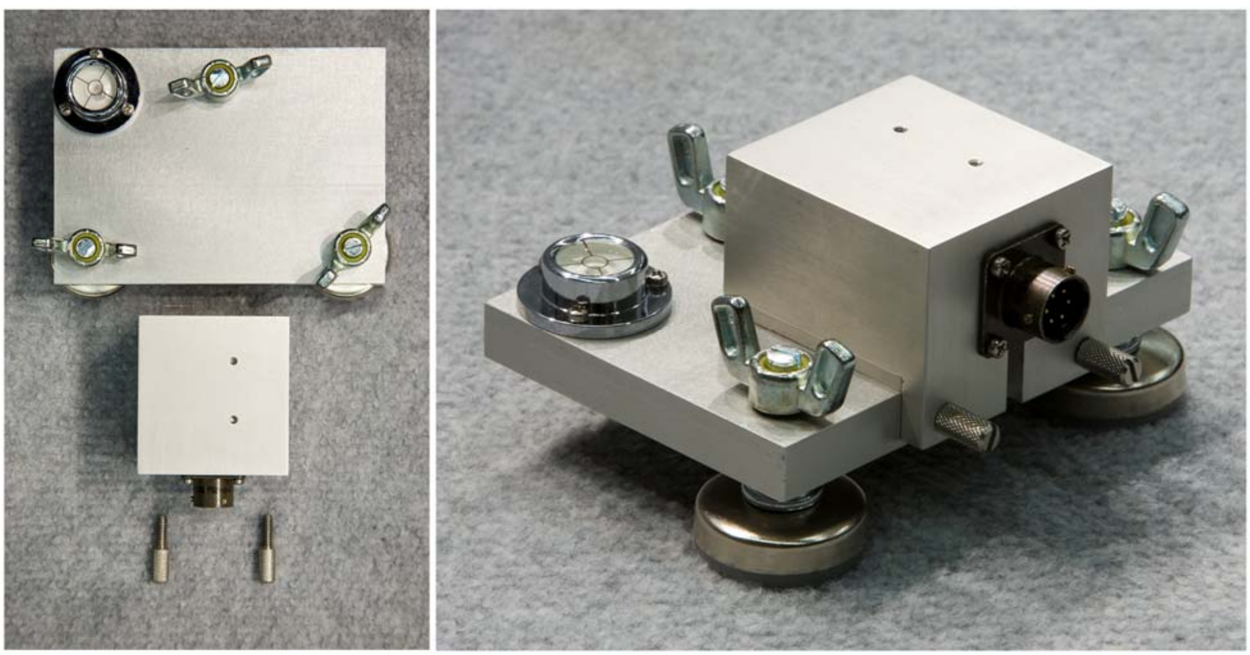

Figure 77. Photo. Accelerometer box attached to calibration platter.

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 39. 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.

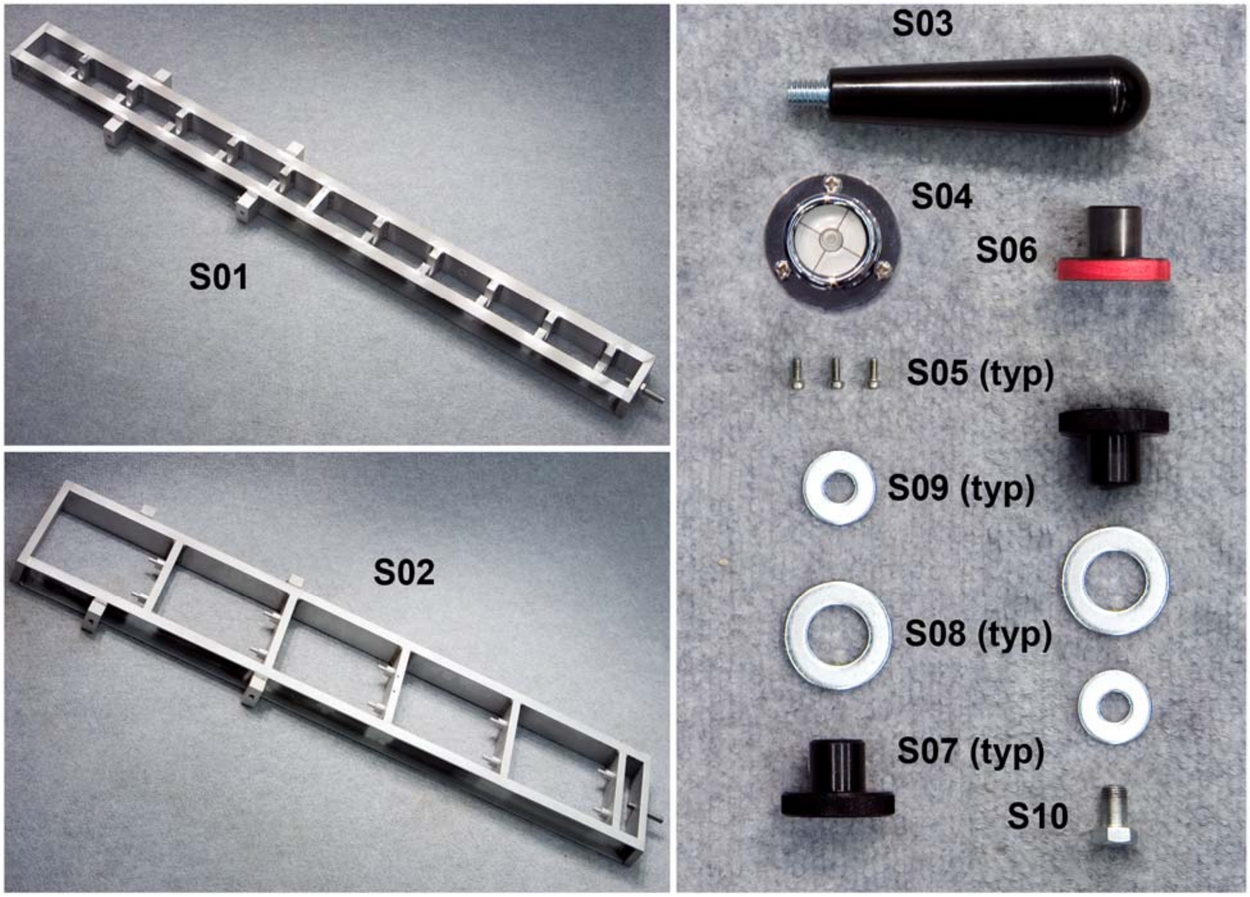

Figure 78. Photo. Equipment for calibration stand assembly.

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 phillips 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 push-button 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 79 for an example.

4. For both the geophone calibration stand and the seismometer calibration stand, the connector pin is fastened to the stand with medium strength Loctite #242. Figure 84 shows the geophone calibration stand with a connector pin attached.

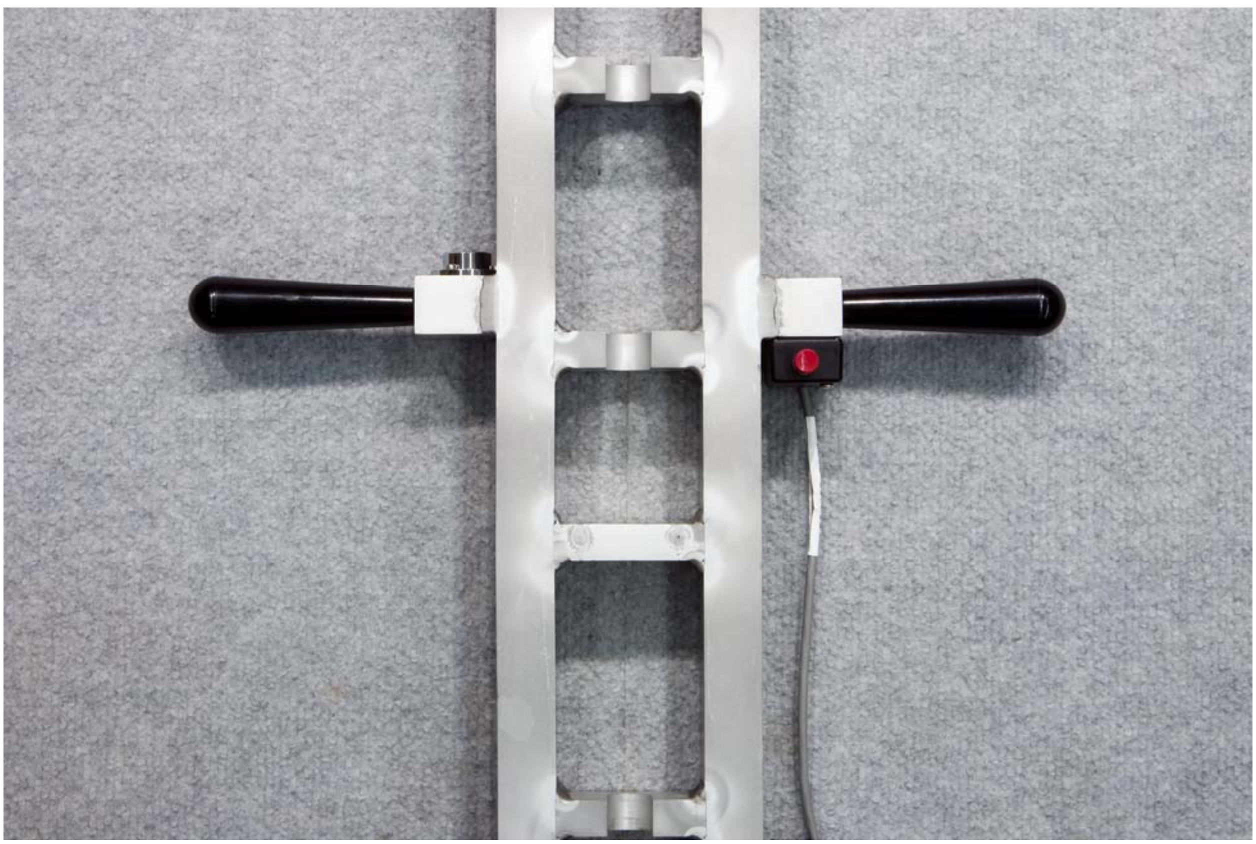

Figure 79. Photo. Calibration stand with handles, bubble level, and pushbutton.

Location of Accelerometer Box

On the geophone calibration stand, the accelerometer box is fastened to a shelf half way up the stand with two #10-24 x 1/2." 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.

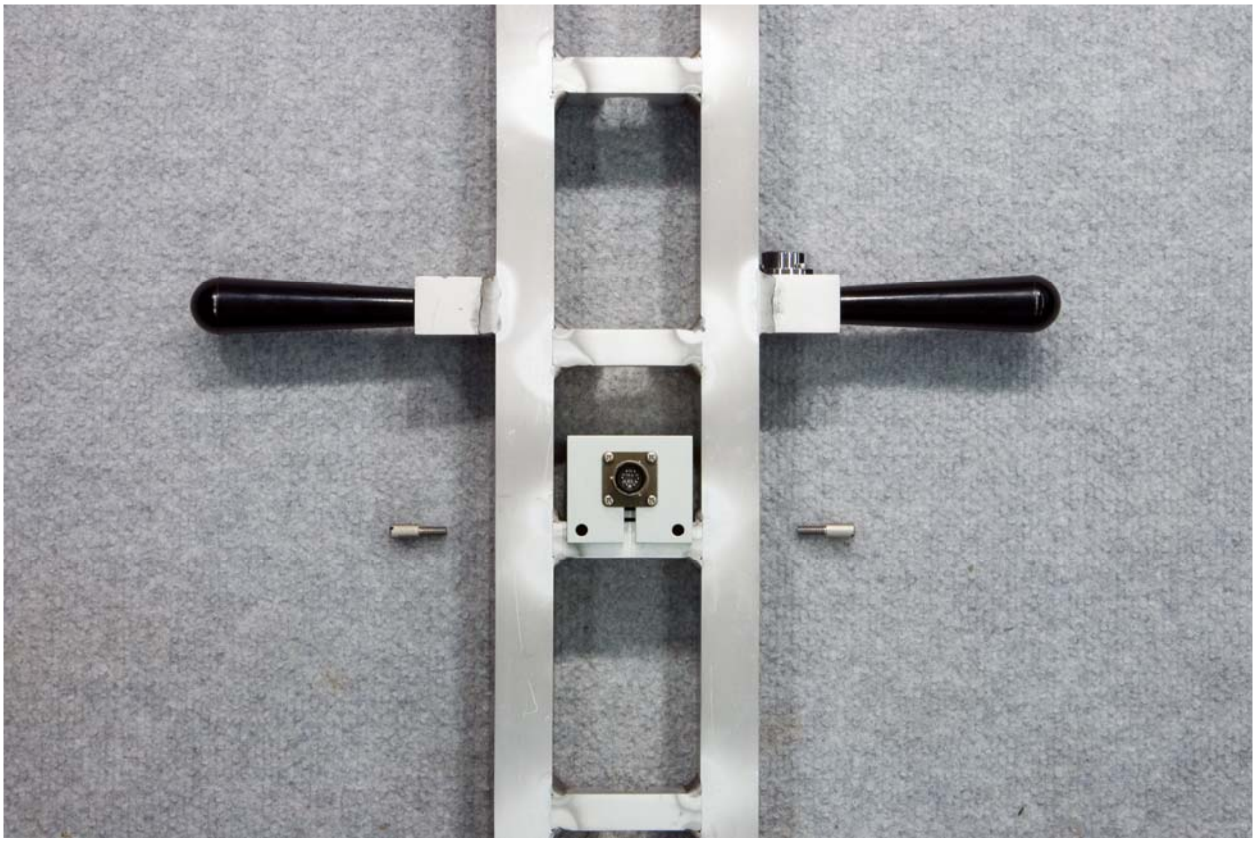

Figure 80. Photo. Placement of the accelerometer box.

Deflection Sensors

For the geophone calibration stand, there are three different types of geophones that can be calibrated, as made by Carl Bro, Dynatest, 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 shelf. Figure 81 shows a JILS geophone and adapter fastened to the stand. Carl Bro geophone adapters (S06) have different size threading and are painted red.

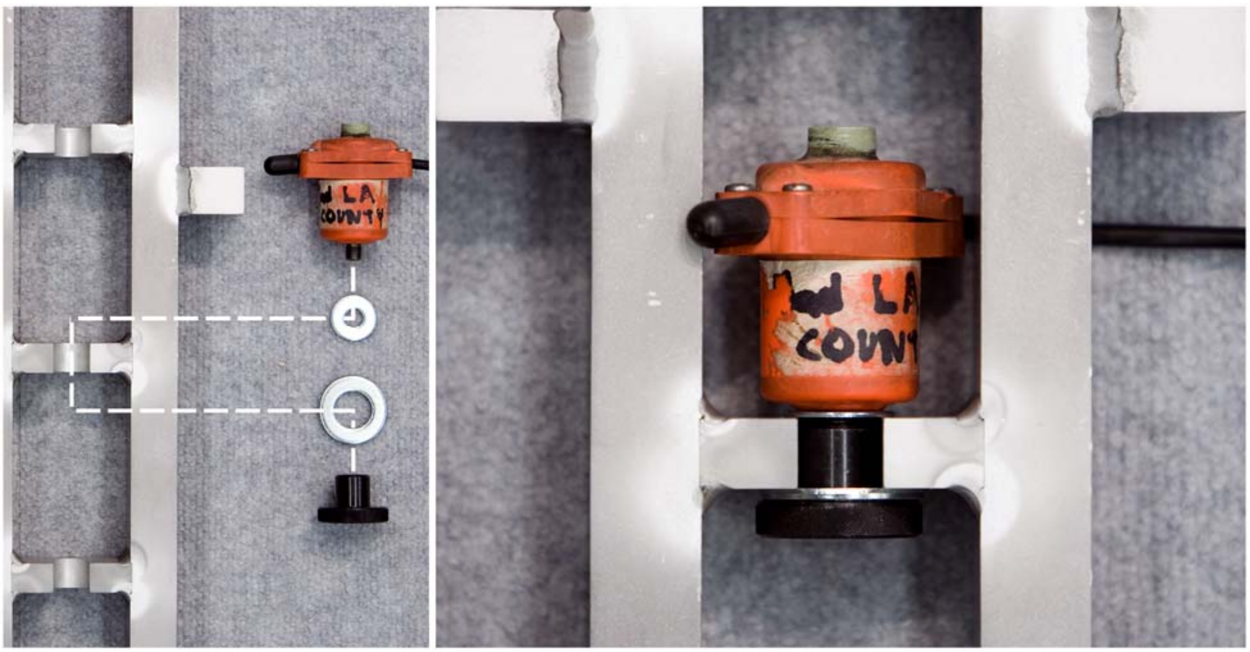

Figure 81. Photo. Attachment of a JILS or Carl Bro geophone.

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 82. The Dynatest geophone then sits on top of the adapter.

Figure 82. Photo. Attachment of a Dynatest geophone.

For the seismometer calibration stand, the seismometers are aligned in a two-column configuration as shown in Figure 83. Tighten the setscrew at the bottom of the seismometer onto the standoffs on the stand.

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 push-button 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 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.

Figure 83. Photo. Seismometer stand with sensors attached.

To couple to the ball joint.

For both calibration stands, the connector pin slides into the clamp as shown in Figure 84. The clamp is then tightened so that the stand cannot be removed.

Figure 84. Photo. Coupling the calibration stand and ball joint.

DATA ACQUISITION EQUIPMENT

Parts and Tools

Table 40. 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 Rev. B
D02	Vishay to Load Cell Cable	1	DWG number CLRP-DAQ02 Rev. B
D03	Accelerometer Signal Cable	1	DWG number CLRP-DAQ03 Rev. C
D04	Push-button to KUSB DAQ Cable	1	DWG number CLRP-DAQ04 Rev. B
D05	Keithley KUSB-3108 16-bit Data Acquisition Board	1	
D06	Vishay 2310 Signal Conditioner	1	

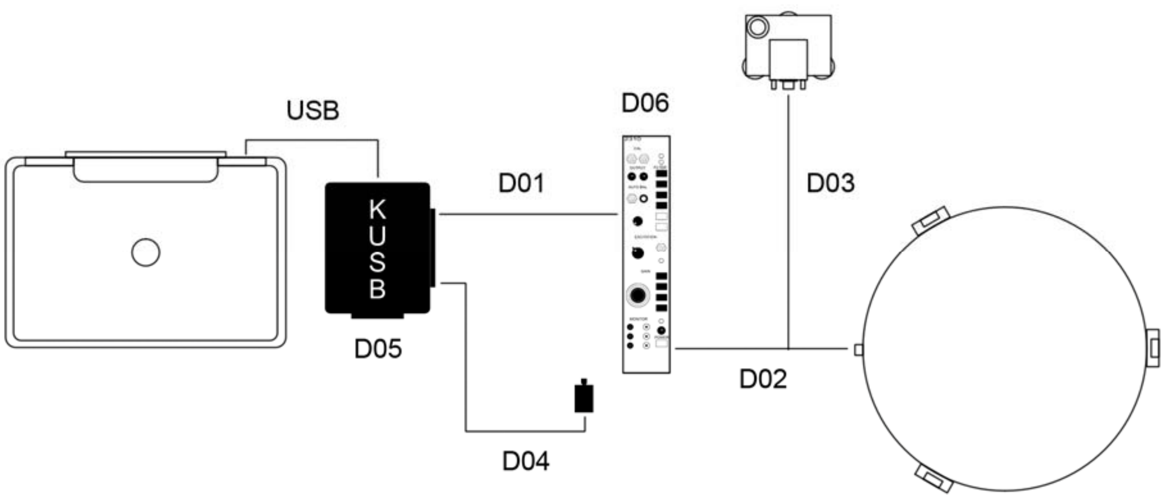

Figure 85. Chart. FWD data acquisition system components and connections.

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 85.

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 center 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.

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.

Push-button 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 41. Settings for the Vishay 2310 signal conditioner when used with load cell and accelerometer.

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 an FWD calibration computer:

Table 42. 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 IV. SOFTWARE OUTLINE

WINFWDCAL

The following flow charts show the general outline of the new calibration software, *WinFWDCal*. The actual Visual Basic code is available upon request from the Federal Highway Administration or Cornell Local Roads Program.

Startup

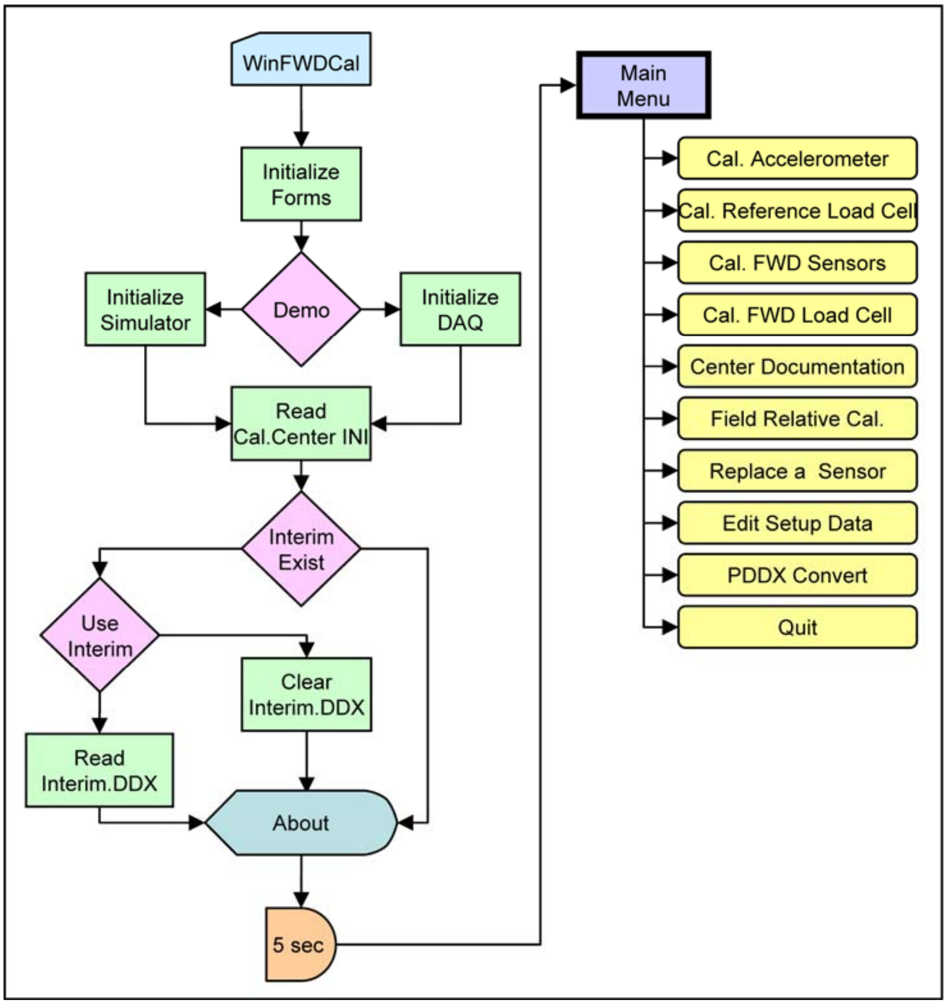

Figure 86. Chart. *WinFWDCal* startup flowchart.

Calibrate Accelerometer

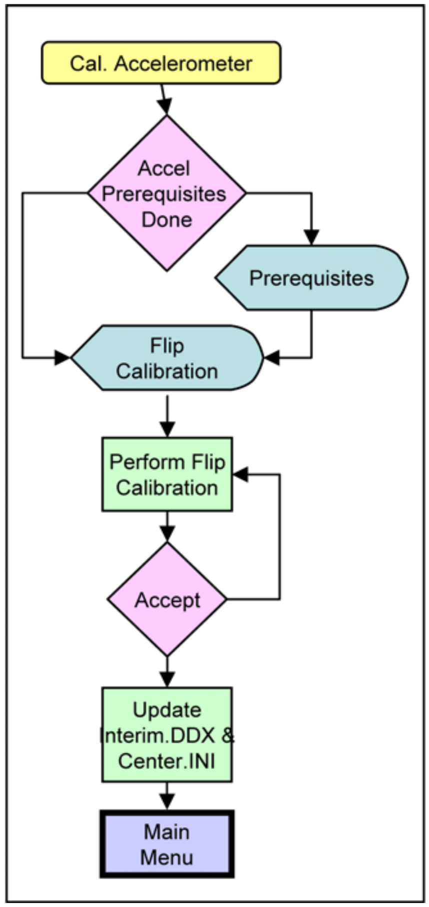

Figure 87. Chart. Calibrate accelerometer flowchart.

Edit Setup Data

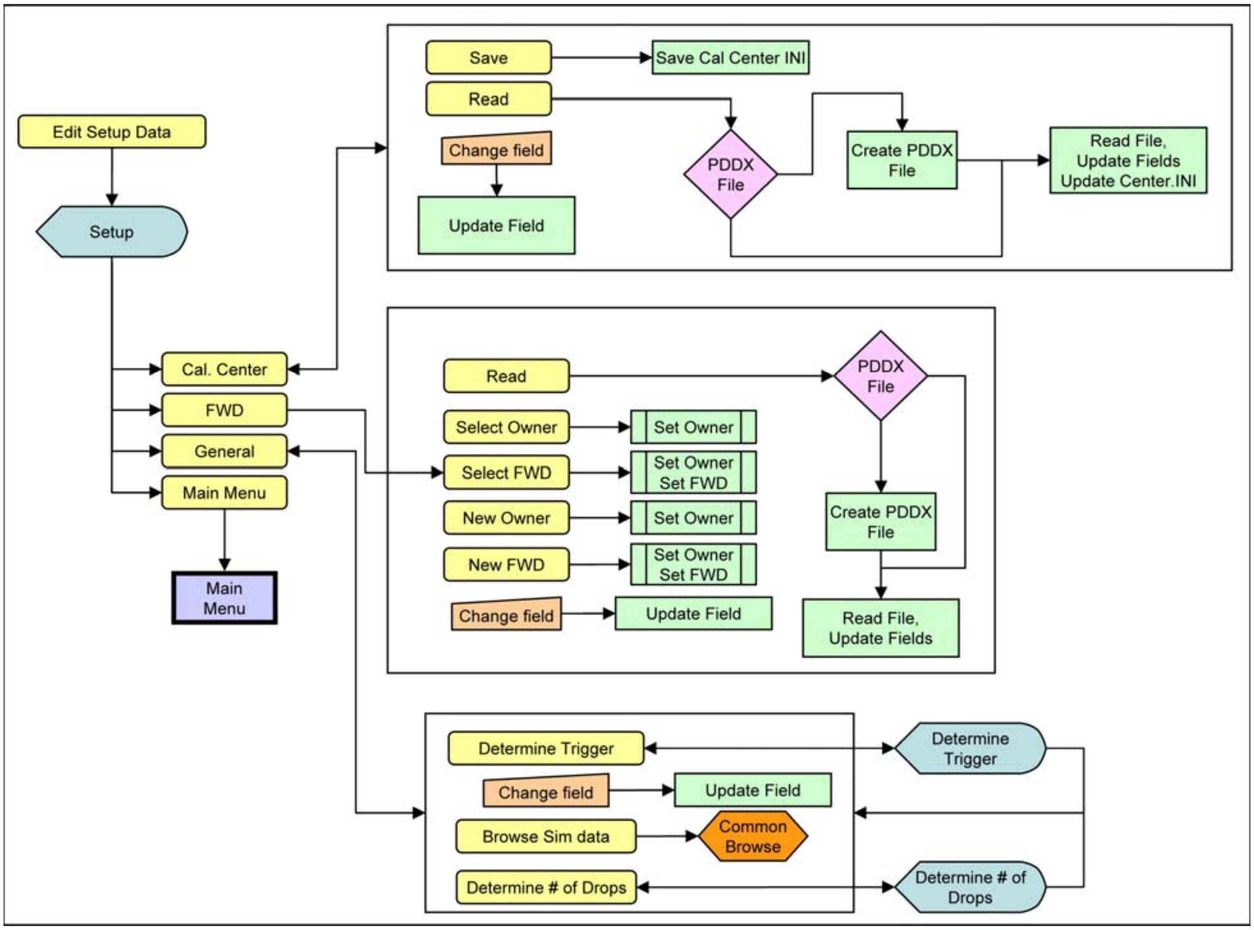

Figure 88. Chart. Edit setup data flowchart.

Determine Trigger and Number of Drops

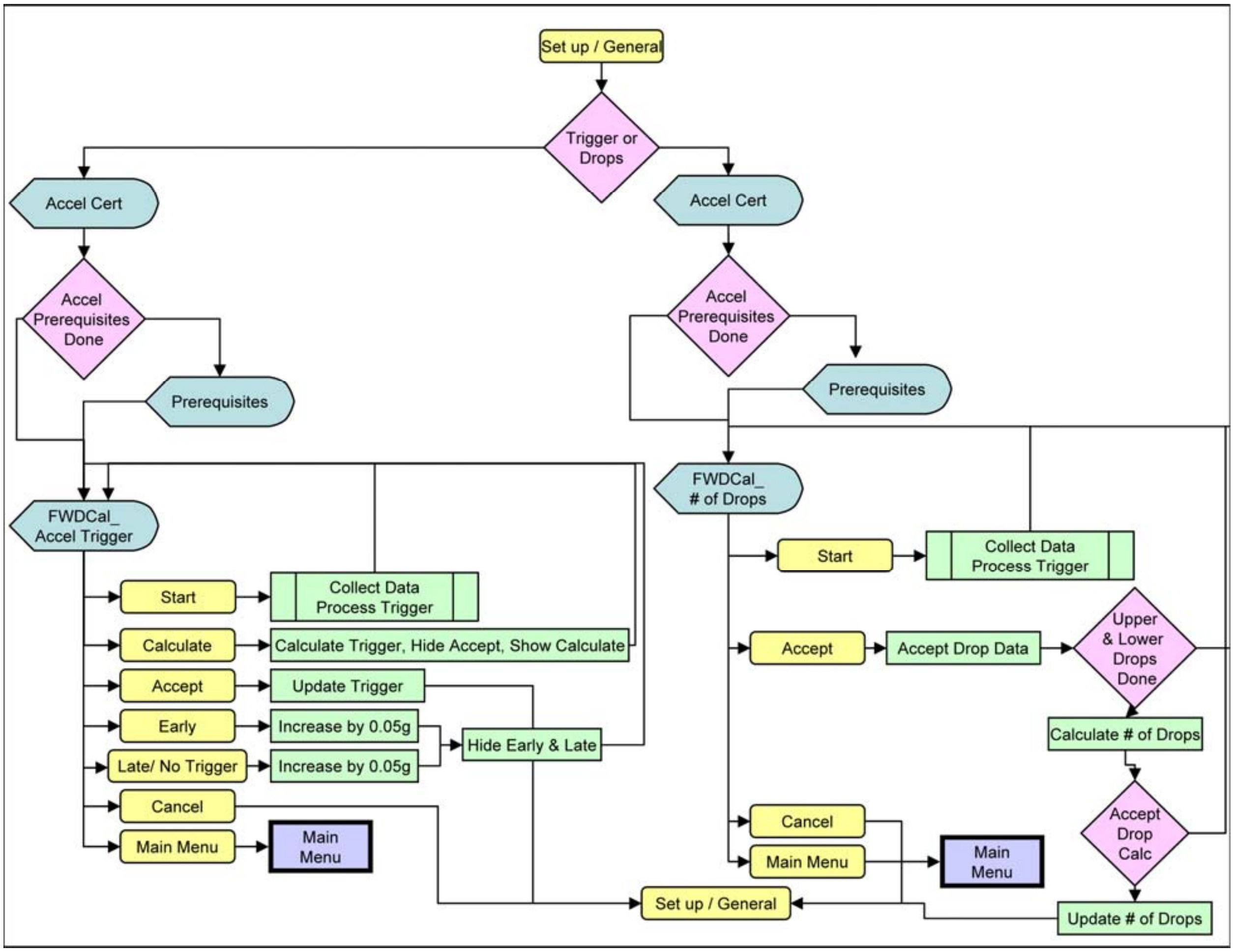

Figure 89. Chart. Determine trigger and number of drops flowchart.

Calibrate FWD Load Cell

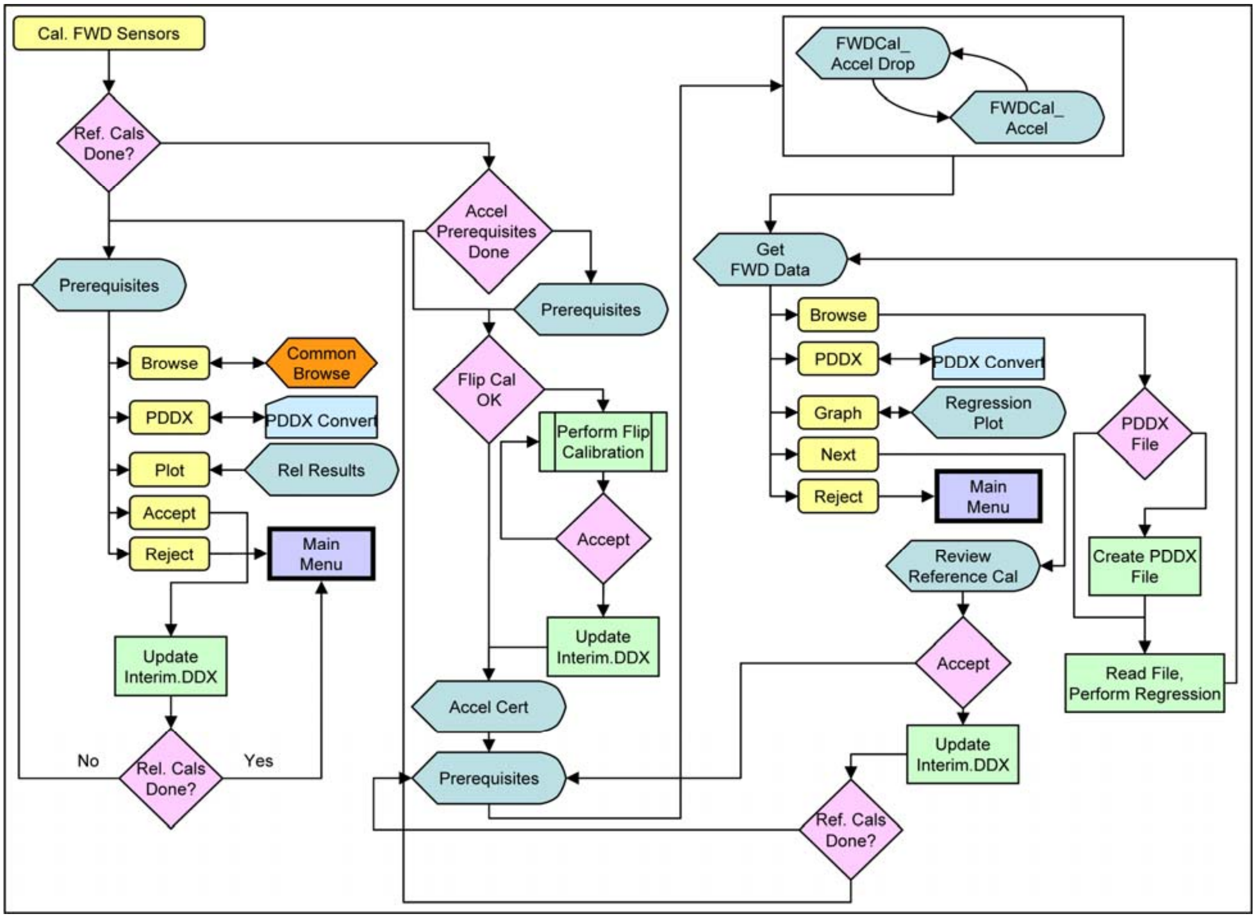

Figure 90. Chart. Calibrate FWD load cell flowchart.

Calibrate FWD Sensors

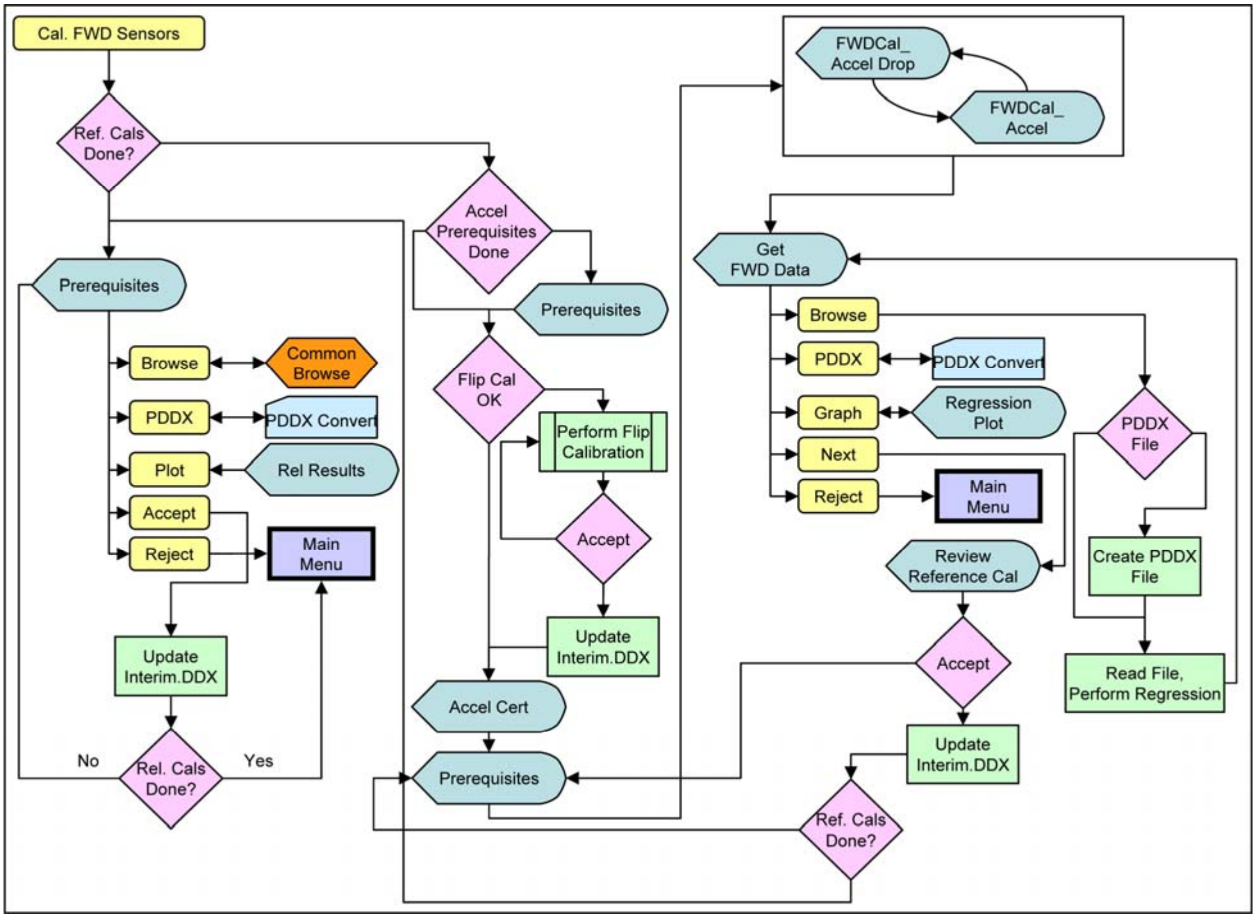

Figure 91. Chart. Calibrate FWD sensors flowchart.

Center Documentation

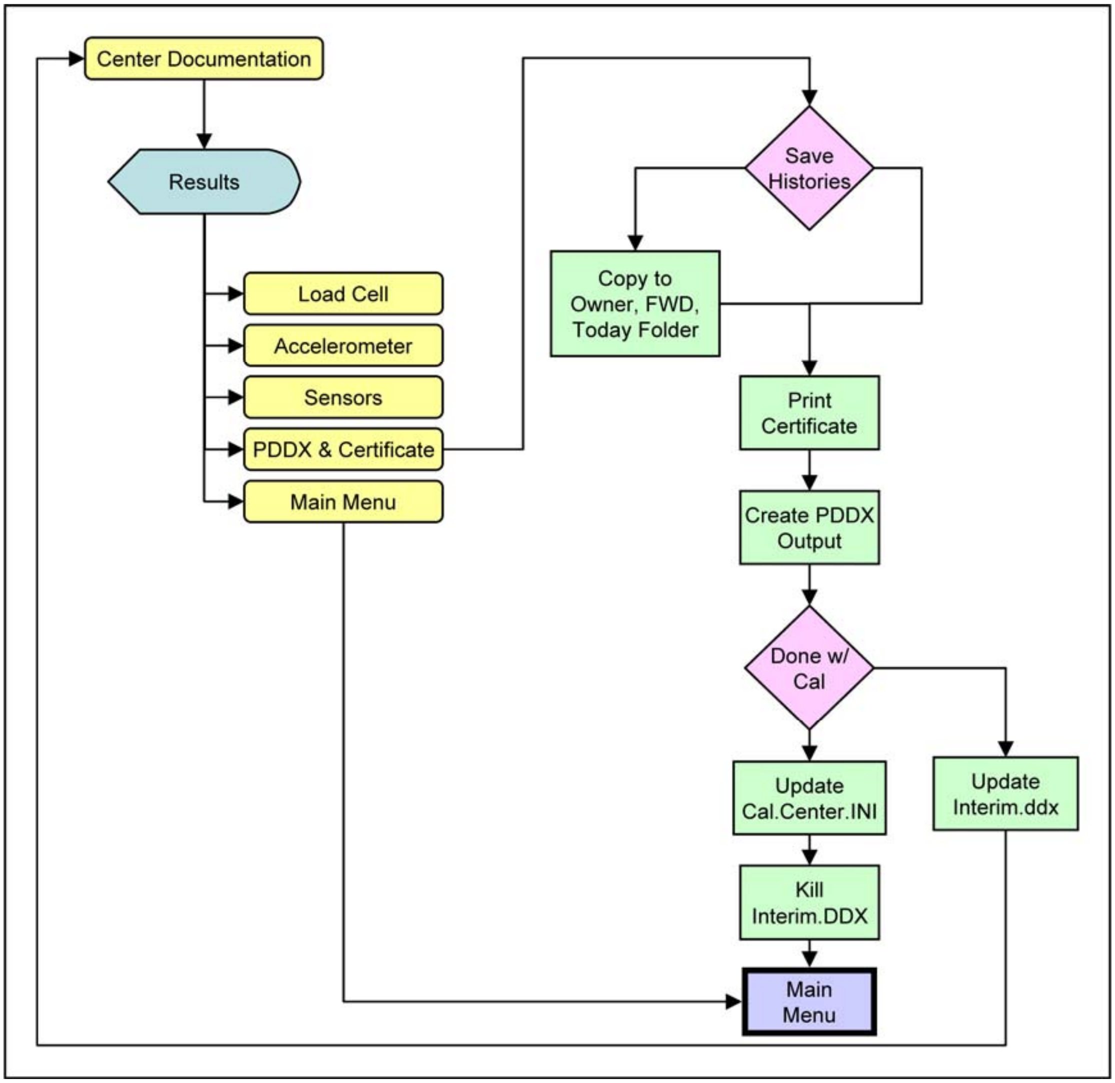

Figure 92. Chart. Center documentation flowchart.

Quit

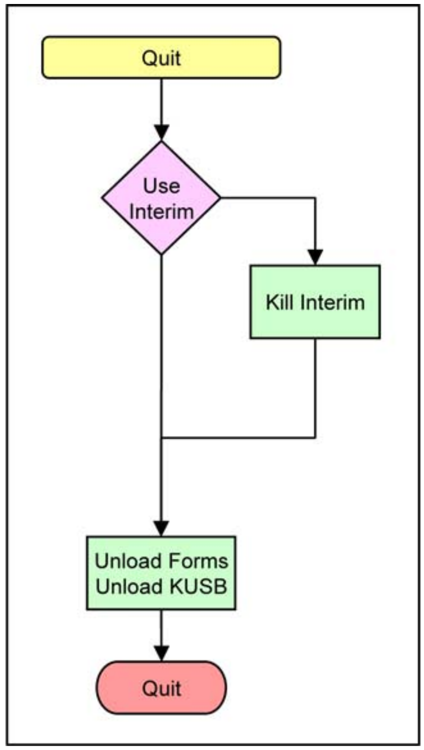

Figure 93. Chart. Quit *WinFWDCal* flowchart.

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