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Full-Scale Barge Impact Experiments, Robert C. Byrd Lock and Dam, Gallipolis Ferry, West Virginia

Robert C. Patev, Bruce C. Barker,
and Leo V. Koestler III

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ABSTRACT: Full-scale barge impact experiments were conducted on a rigid upstream guide wall at Robert C. Byrd Lock and Dam (Old Gallipolis Lock) in Gallipolis Ferry, WV. The primary goal of these experiments was to measure the actual impact forces normal to the wall using a load-measuring device. Additional objectives of these experiments were to obtain and measure the baseline response of an inland waterway barge, quantify a multi-degree-of-freedom system during impact, and investigate the use of energy-absorbing fenders. The full-scale experiments used a 15-barge commercial flotilla. The barges were jumbo open-hopper rake barges (35 by 195 ft; 11 by 59 m) and were ballasted with coal to a draft of 9 ft (2.5 m). The total mass of the flotilla was approximately 27,000 metric tons.

Instrumentation similar to that used during the "prototype" experiments, performed in August 1998, was used for the full-scale experiments. This included accelerometers, strain gages, and clevis pin load cells in the lashing parts. The instrumentation data were collected using over 80 channels of instrumentation on both the barge and lock wall. These experiments also utilized a differential global positioning system (DGPS) on the flotilla to measure the tow velocity, angle, and rotation during impact, as well as high-speed cameras to capture the barge-wall and barge-fender interaction.

New state-of-the-art instrumentation was developed to measure the actual load normal to the barge and wall. This consisted of a load-measuring beam that had two clevis pin load cells capable of measuring up to approximately 1,200 kips (5,340 kN). In addition, a system of polyvinylidene fluoride (PVDF) sensors was developed at the U.S. Army Engineer Research and Development Center as part of a redundant load-measurement system on the load beam.

Forty-four impact experiments were successfully conducted on both the rigid concrete upper guide wall (baseline and load-measuring device) and on the prototype fendering system (baseline and load-measuring device). A matrix of the required angles and velocities was assembled for the comparison between the baseline and load-measuring experiments on both the concrete and prototype fendering systems. This matrix was successfully filled for each impact case during these 44 experiments. The final matrix contained angles of impact from 5 to 25 deg, with velocities from 0.5 to 4 ft (0.15 to 1.2 m) per second.

The report includes detailed explanations of the instrumentation used, including data acquisition systems, barge and lock wall instrumentation, DGPS, and high-speed camera and videotape equipment. Design concepts and installation of the prototype fendering system used in the experiments are also discussed. Conclusions and recommendations are presented, in support of the future numerical modeling and data interpretation efforts. Appendixes to the report present a selected collection of raw data plots from the baseline and load beam experiments.

Contents

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	25.4	millimeters
kips (force)	4.448222	kilonewtons
miles (U.S. statute)	1.609347	kilometers
tons (short), 2000 lb)	907.1847	kilograms

Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Innovations for Navigation Projects (INP) Research Program, Work Unit (WU) 33143, "Design of Innovative Lock Walls for Barge Impact." This research was initiated by Mr. Robert C. Patev, former Principal Investigator of WU 33143. Current Principal Investigator is Dr. Robert M. Ebeling of the U.S. Army Engineer Research and Development Center (ERDC) Information Technology Laboratory (ITL).

Dr. Tony C. Liu was the INP Coordinator at the Directorate of Research and Development, HQUSACE; Research Area Manager was Mr. Barry Holliday, HQUSACE; and Program Monitors were Mr. Mike Kidby and Ms. Anjana Chudgar, HQUSACE. Mr. William H. McAnally of the ERDC Coastal and Hydraulics Laboratory (CHL) was the Lead Technical Director for Navigation Systems; Dr. Stanley C. Woodson, ERDC Geotechnical and Structures Laboratory (GSL), was the INP Program Manager.

This research was performed and the report prepared by Mr. Patev, U.S. Army Engineer District, New England, and Messrs. Bruce C. Barker and Leo V. Koestler III, Engineering and Informatic Systems Division (EISD), ITL.

The authors wish to acknowledge the dedicated efforts of those professionals who demonstrated true teamwork during many weeks in the field to successfully install instrumentation and collect the necessary data and information. Members of the ERDC Barge Impact Team include Messrs. Wallace Gay (retired), Tony Brogdon, and Terry Warren, EISD; Mr. David Gary Dill and the late Mr. David Ray, Multimedia Presentation Branch, ITL; Messrs. Don Wilson, Terry Waller, and David Maggio, Navigation Section, CHL; and Mr. Vince Chiarito, Structural Engineering Branch, GSL.

The research was conducted under the supervision of Dr. Charles R. Welch, Chief, EISD; Mr. H. Wayne Jones, Technical Directors' Office, ITL; Dr. Jeffery P. Holland, Director, ITL; and Dr. David W. Pittman, Acting Director, GSL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL James R. Rowan, EN, was Commander and Executive Director.

1 Introduction

Inland waterway navigation structures at U.S. Army Corps of Engineers lock and dam facilities are inherently subjected to usual or daily barge impact loads due to transiting flotillas. However, barge impact forces for unusual and extreme events such as operator error, loss of power, or loss of control have dramatically influenced the current Corps designs loads for inland waterway structures (Patev 1999). This increase in design loads for barge impact has created a significant increase in the overall costs of navigation structures.

The existing analytical models used by the Corps for the analysis and design of barge impact loads are thought to be overly conservative for use in design. With the design trend in the Corps toward building thinner walled innovative structures, the quantification of barge impact forces becomes a critical part in the success of this innovative design (Patev 1999). Until recently, the true quantification of the force between an inland waterway flotilla and a concrete lock wall had never been accomplished in full-scale experiments.

The purpose of these full-scale experiments was to measure the actual impact loads normal to the wall of a 15-barge ballasted flotilla. These experiments will greatly assist in quantifying the behavior (i.e., flexibility and motion of barge trains) of an inland waterway tow during an impact into a lock wall. Previous full-scale experiments termed “prototype” (performed by Patev, Barker, and Koestler 2002) used a four-barge ballasted tow. These experiments were very beneficial in defining the instrumentation system for the full-scale experiments, and provided important information as to barge behavior during impacts. Observations and recommendations made in Patev, Barker, and Koestler (2002) were incorporated into these experiments to ensure a successful experimental program.

2 Background

2.1 Barge Impact Models

The Corps’ barge impact design methodology for inland navigation structures is documented in Engineer Technical Letter 1110-2-338, “Barge Impact Analysis” (rescinded 1999), referred to hereafter as “ETL 338.” The model defined in ETL 338 bases the barge and wall as a two degree-of-freedom (TDOF) system. The TDOF system is shown in Figure 2.1. The only input required to this TDOF model is the mass, size (beam and length), velocity, and angle of impact of the flotilla. The ETL 338 model has been developed for both rigid and flexible structures and is based on a constant pressure coefficient developed by Minorsky (1959). The Minorsky model uses a “kinetic energy lost” to “damage volume” relationship for ship collisions. This model also assumes permanent deformation of a ship hull.

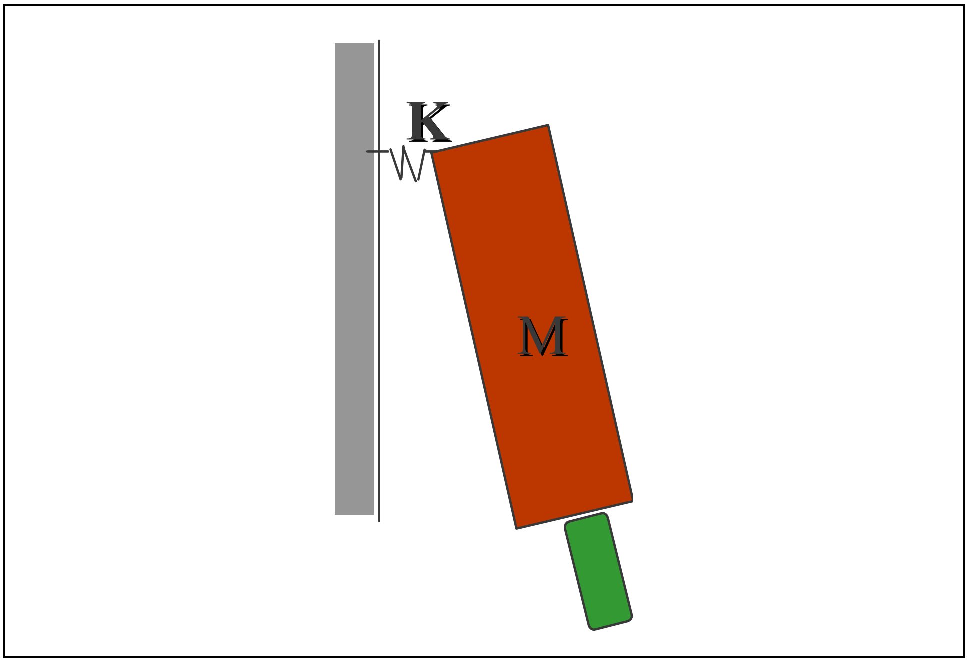

Figure 2.1. TDOF barge system in ETL 338

Unfortunately, the model developed in ETL 338 has significant limitations. First, the existing TDOF model does not account for the flexibility of the flotilla during impact on a navigation structure. This flexibility of a tow is accounted for by the lashings (or wires) that tie the flotilla together. The true system is represented by a multi-degree-of-freedom (MDOF) system, as shown in Figure 2.2.

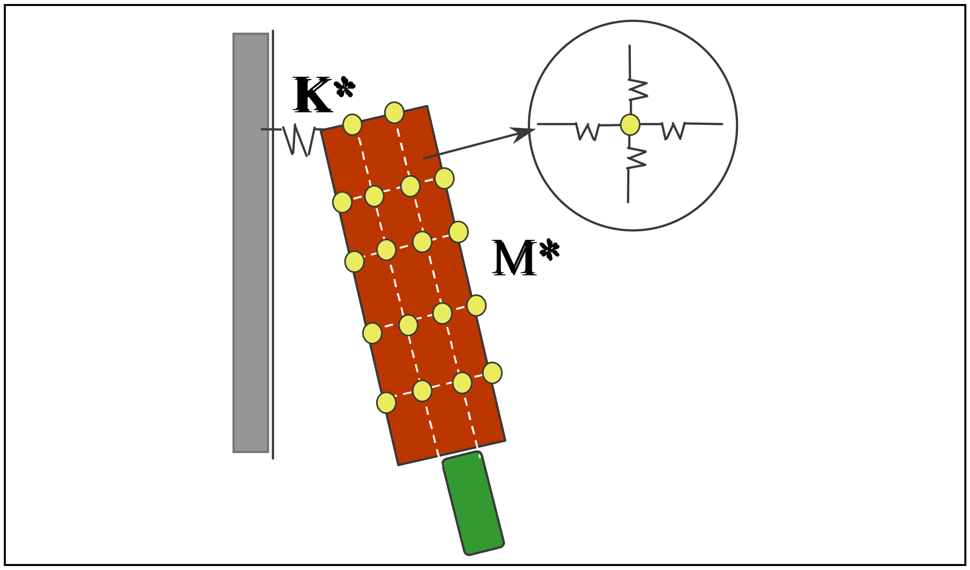

Figure 2.2. MDOF barge system

The second limitation is that the model is based on permanent deformations of the barge corner. These types of deformations are not typically the norm for inland waterway barges and are very rarely encountered on the inland waterway during most usual and even during the most unusual impact events.

Third, the model also requires a correction to the stiffness function based on the Minorsky coefficient for small angles (less than 2 deg[1]) and large angles (greater than 80 deg). This correction has created a limited use of this model for the head-on impacts into bullnoses and protection cells at Corps facilities as well as very careful interpretation of the resulting impact forces at small angles.

Last, this model is based primarily on impact research for deep-draft vessels and has had no field verification or validation to typical inland waterway flotillas. These limitations of the model, combined with the consensus that this model produces very conservative design loads, are the basis of Corps' making a focused effort to perform both prototype and full-scale barge impact experiments.

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[1] A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page v.

2.2 Prototype Barge Impact Experiments

The prototype barge impact experiments were conducted on an old lock wall at Allegheny River Lock and Dam 2 in Pittsburgh, PA. These experiments were termed prototype because this type of full-scale experiment using an inland waterway flotilla has never before been attempted. The goals of these prototype experiments were to learn how to quantify and measure barge impact forces and to understand the complexity of the barge-wall system during impact. The observations and results from these prototype experiments are discussed and documented further in Patev, Barker, and Koestler (2002).

These experiments used four standard (27- by 195-ft) open-hopper rake barges. The barges were drafting to 8.5 ft and had a combined mass of around 4,000 short tons. The impact experiments were accomplished on a rigid massive concrete wall and on friction-less ultra-high molecular weight (UHMW) plastic fenders. The UHMW fenders were used to investigate the redistribution of the barge energy and direction during impact. A total of 36 impact experiments (25 on the concrete and 7 on the UHMW fenders) were successfully completed and documented.

The experiments utilized 15 instrumentation devices recorded on 28 channels on both the flotilla and lock wall. The instrumentation included accelerometers and strain gages on the lead corner barge, as well as clevis pin load cells spliced into the lashings. These clevis pin load cells measured the change in tensile force in the lashing parts upon impact. A multi-unit differential global positioning system (DGPS) was also used to measure the velocities (normal and tangential), impact angle, and rotation of the flotilla during impact. A high-speed camera (100 frames per second) and a videotape camera were set up to document the interaction of the barge-wall system upon impact. Overall, these experiments were very valuable in providing a better understanding of the dynamics of the barge-wall system and contributed vital data and knowledge that could be used for the full-scale barge impact experiments.

3 Experiment Site – Robert C. Byrd Lock and Dam (Old Gallipolis Locks)

3.1 Introduction

Robert C. Byrd Lock and Dam is situated on the Ohio River about 279.2 miles below Pittsburgh, PA, and 9 miles below the city of Gallipolis, OH. The original Gallipolis Lock and Dam was operational in August 1937 and replaced Locks and Dams (L&D) 24, 25, and 26 on Ohio River and L&D 9, 10, and 11 on the Kanawha River. The original structure has two parallel lock chambers: a main lock, 110 by 600 ft and an auxiliary lock 110 by 360 ft. The dam at Gallipolis Lock is a nonnavigable, high-lift, gated dam with a top length of gated section of 1,132 ft. The dam is gated with eight roller gates that have a clear span of 125 ft, 6 in., between 16-ft piers with a damming height of 29 ft, 6 in., above gate sills. The normal lift for the locks is 23 ft.

As the result of numerous barge accidents into the dam from poor hydraulic conditions and outdrafts at Gallipolis Locks, a new set of locks were authorized under the Supplemental Appropriation Act of 1985 and the Water Resources Development Act of 1986. The new locks, Robert C. Byrd Lock and Dam, are adjacent to the Gallipolis Lock site. The construction on the new locks started in 1987, and the lock was fully operational in 1993. This replacement lock added two additional lock chambers: a main chamber that is 110 by 1,200 ft and an auxiliary chamber that is 110 by 600 ft. The lock chambers at the Gallipolis Lock were closed off by cellular bulkhead structures and decommissioned in 1993. The location of both locks (Gallipolis and Robert C. Byrd) is shown in Figure 3.1.

The location of the site for the full-scale experiments, Old Gallipolis Lock, was selected because the locks and adjoining lock walls were decommissioned in 1993 when the two new lock chambers were put into operation. After much investigation and discussion, this site was the only lock facility on any major waterway that is still owned and maintained by the government. The chambers are currently used to house various Corps Ohio River maintenance fleet vessels and their activities.

Figure 3.1. Aerial view of Robert C. Byrd Lock and Dam (Old Gallipolis Locks are adjacent to the dam near the middle of the picture)

The concrete approach walls at Gallipolis Lock were still fully intact and operational. The wall selected for the impact experiments would be the upper guide wall. The upper guide wall was considered a rigid structure since it was founded on rock and backfilled up to pool level. The point of impacts on the upper guide wall was centered near the 950-ft mark (i.e., 950 ft upstream of the main chamber). Unfortunately, the upper 500 ft of timber-cribbed guide wall above the impact location was removed to make room for the filling intakes for the new locks. This would have allowed testing to be performed on a more flexible wall system as well. The upper guide wall is shown in Figure 3.2.

In addition to having a rigid concrete lock wall, the Gallipolis Lock chambers could be used as staging facilities for the assembly of the fenders and impact load bumper. The lock facility also had a barge crane that could be used to install the prototype fendering system onto the lock walls.

Some of the primary benefits of using Gallipolis Lock for the full-scale experiments were

a. An intact decommissioned lock.

b. Rigid concrete lock wall.

c. Outside a navigable inland waterway.

d. Available staging facilities.

e. Available barge crane and crew onsite.

f. Close access to shore for lock wall instrumentation.

g. Safe tie-up location and change-out facility for barges and towboat.

h. Proximity to coal industry facilities.

Figure 3.2. Upper guide wall at Gallipolis Lock (Note: As reference, prototype fenders are on the left; lock chambers are straight in the distance; and the dam is on the right)

4 Towboat and Barges

4.1 Introduction

The full-scale experiments were originally planned and contracted with industry to occur during August 24-28, 1998. This week was selected because it is traditionally a slower time of year for the barge industry, and the flows of the Ohio River tend to be at a minimum. The industry partner, American Commercial Barge Lines (ACBL) of Jeffersonville, IN, had to cancel its participation in the experiments due to unexpected early requests for coal at the power plants along the Ohio River. This left the full-scale experiments without barges and a towboat.

A new industry sponsor, American Electric Power (AEP) of Columbus, OH, was found in October 1998. AEP kindly donated the services of a 15-barge commercial tow. They (like ACBL) became busy stocking their coal piles for the anticipated cold winter. The best time for AEP to assist with the experiments was during early December. December was not the optimum month for the experiments because the weather is usually colder and windier than during August, and the risk of outdrafts at the Gallipolis locks is greatly increased.

The preinstallation of the instrumentation on the two corner barges occurred at the AEP maintenance facility during the period November 16-25, 1998. AEP released a commercial tow to assist in the full-scale experiments for a 3-day period, as opposed to the originally planned 5-day period. This period was December 1-3, 1998. The shortened schedule caused the experiments to be slightly abbreviated, so that we could maximize the time with the commercial tow for the types and number of experiments that could be performed.

4.2 Flotilla Information

The full-scale experiments used a 15-barge commercial flotilla. The barges were jumbo open-hopper rake barges (35 by 195 ft) and were ballasted with anthracite coal to a draft of 9 ft. The flotilla was in a 3-wide by 5-long barge configuration, which is typical for an inland waterway tow. The front and last rows of the flotilla were single-raked barges (i.e., rake in the front, flat in the back). The middle three rows were double-raked (i.e., raked at both ends). The barge rake is actually on a 35-ft radius but typically runs at an average angle of 23 deg.

The width of the flotilla was 105 ft, and the length of the flotilla (not including the towboat) was 975 ft. A view of the barges from the captain's position in the towboat is shown as Figure 4.1.

Figure 4.1. View of 15-barge flotilla from deck of towboat

The use of the barges and a 2,800-hp towboat, the MS *Jeffery V. Raike*, was arranged under a partnership agreement with AEP River Transportation Division of Lakin, WV. The primary towboat is shown in Figure 4.2. A helper boat was also needed in case of emergency with the prime vessel or breakup of the flotilla during impact. The helper boat, an 1,100-hp towboat, the MS *Quaker State*, was supplied by Kahawa River Towing of Point Pleasant, WV. A picture of the helper boat is presented as Figure 4.3. The entire flotilla (15-barge tow and helper boat) is shown in Figure 4.4.

The experiments required the use of two separately instrumented barges. One barge was for baseline response measurements of a barge impacting a lock wall; the other was instrumented with the load beam to measure the actual load normal to the wall. The lead corner barges were constructed in 1993 by Nashville Bridge (now Trinity Barges) for AEP and carried the AEP barge identification Nos. 9271 and 9264. These barges were selected for the experiments since they were considered rather new (in river terms, where the average age of a barge is 20 years) and had little or no damage to the corner.

Figure 4.2. Primary towboat, MS Jeffery V. Raike

Figure 4.3. Helper towboat, MS *Quaker State*

The layout of the 3- by 5-barge configuration is shown in Figure 4.5. The helper boat is shown on the starboard side of the flotilla. The label in each cell indicates the barge ID number used in the manifest for the vessel. Each manifest also contains the weight of each barge, tare mass of each barge, type of barge, and commodity. As shown in Table 4.1, the total mass of the flotilla (including towboats) was approximately 30,000 short tons.

Figure 4.4. Entire flotilla, 15-barge commercial tow and helper boat

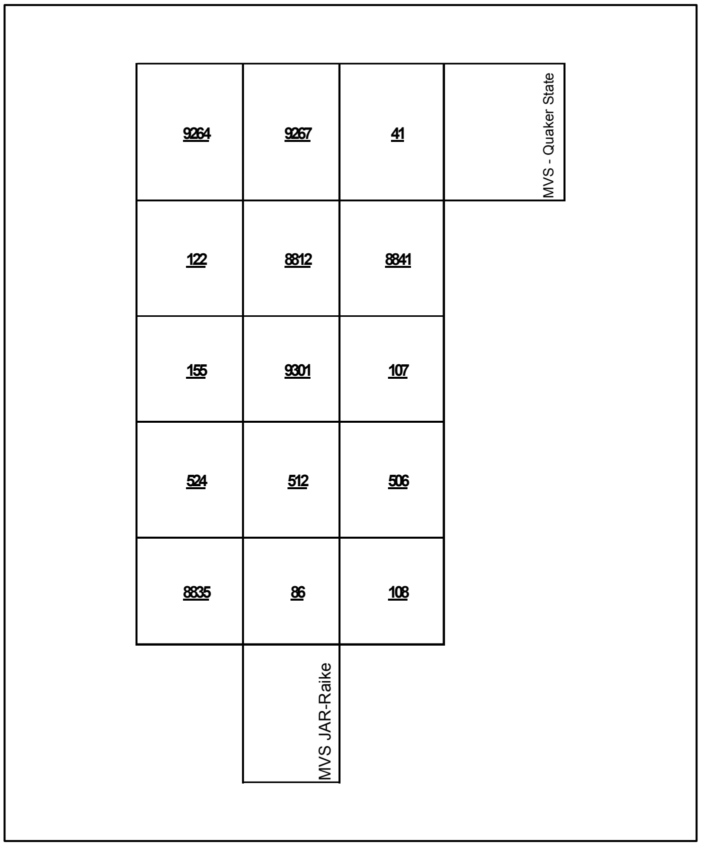


Figure 4.5. Barge layout and configuration for experiments

Table 4.1
Barge Masses for Flotilla

Barge	AEP Barge ID Number	Coal in barge (tons)	Tare of barge (tons)
1	9,264	1,521.93	284
2	9,267	1,544.33	284
3	41	1,556.33	273
4	122	1,555.88	296.9
5	8,812	1,555.52	303
6	8,841	1,444.76	298
7	155	1,676.12	296.9
8	9,301	1,675.5	284
9	107	1,666.7	296.9
10	524	1,788.23	304
11	512	1,788	304
12	506	1,899.45	304
13	8,835	1,673.9	303
14	86	1,676.95	296.9
15	108	1,676.25	296.9
		24,699.85	4,425.5
Total for barges		29,125.35	
MVS JAR-Raike		550.55	
MVS - Quaker State		335.89	
Total for flotilla		30,011.79 tons	

4.3 Operation of Tow During Experiments

Since these experiments used a commercial tow on the way to deliver coal to an AEP power plant downriver, the experiments needed to be executed under rather strict control and operation, as well as high standards for the safety of the personnel onboard. A set plan of instructions (including emergency plans) was agreed upon prior to the experiments. This plan was developed jointly by the captain of the flotilla, the captain of the helper boat, AEP's port captain, and researchers from the U.S. Army Engineer Research and Development Center (ERDC). The captain of the AEP towboat was in full control of the flotilla during the experiments.

The goal of the instructions and procedures was to permit the tow to approach the wall at a set angle and speed, as required by the impact matrix developed prior to the experiments. The procedure followed the general guidelines:

a. Each angle and speed for each experiment was set up based upon the position of the tow after backing up from the last experiment (unless it was the start of the testing day).

b. Before any motion forward of the flotilla, the decks of the barges were cleared of all personnel, except for the front portions of the lead barges that were used for instrumentation. This was for safety purposes in case a lashing broke during an impact (which did occur during Experiment 5).

c. Radio silence was mandated for a 5-sec period prior to and after impact, unless an emergency situation arose. This silence would permit no radio interference with the trigger for the instrumentation systems.

d. It was requested that the flotilla maintain a constant speed prior to impact without excessive accelerations. The speed of the vessel was determined using a real-time GPS system onboard the AEP towboat. Angles were provided by readings from a transit on the lock walls.

e. Immediately after the primary impact into the wall and radio silence was cleared, the helper boat would assist the main tow by trying to slow down the momentum. This was achieved by using the thrust of the helper boat into the lock walls to invoke more friction on the lock walls. Once momentum was slowed, the helper boat pulled the head of the tow off the walls and assisted with backing up for the next experiment.

f. The flotilla was then backed up to a required distance from the impact zone, and the next angle and velocity from the experiment matrix was selected. This permitted minimum return time between impact experiments.

5 Instrumentation

5.1 Introduction

Most of the instrumentation used in the full-scale experiments was similar to that used in the prototype experiments, as described in Patev, Barker, and Koestler (2002), with the exception of the load beam measuring instrument described later in this chapter. A total of 54 measurements were made on the tow, with an additional 13 response measurements on the lock wall, for each impact test. These instruments included triaxial capacitive accelerometers on the impact corner; servo accelerometers to monitor motion throughout the tow; strain gages installed on the steel plates in the impact corner; clevis pin load cells in the lashings; and two pressure cells to monitor any hydrodynamic loading effects.

For all piezoresistive-type devices (strain gages, clevis pin load cells, and pressure gages), gage excitation, shunt calibration, signal amplification, and filtering conditioning were done using commercial strain gage amplifiers. The onboard analog prefilters were set for 1,000-Hz cutoff. Data were sampled and recorded at 5 kHz (5,000 samples per second) using a 12-bit, National Instruments, PC-based recording system. The software controlling the data acquisition system was developed in-house at the ERDC.

5.2 Data Acquisition Systems

The instrumentation systems used for the full-scale barge impact experiments consisted of two computer-based data acquisition systems—one located in an enclosure on the middle lead barge on the tow; the other in a trailer onshore adjacent to the lock wall. Figure 5.1 shows the location of the flotilla instrument enclosure on the middle lead barge. Fifty-four channels of acceleration, strain, force, and pressure measurements were fielded on the barges, while an additional 13 channels of acceleration and displacement were fielded on the lock wall. As discussed, two impact barges were instrumented for these experiments. One barge used the load measuring bumper mounted on its impact corner, and the other barge did not. The barge without the bumper was used for the baseline response measurements on both the lock wall and prototype fendering system.

Figure 5.1. Onboard instrumentation enclosure on middle lead barge (Note: barge impact corner is just to the right of the picture)

Also, two impact zones on the upper guide were used. The first was on an exposed mass concrete surface (with no wall armor). The second impact location was on a prototype energy-absorbing fendering system, as discussed in Chapter 6. Figure 5.2 shows the locations of impact zones and fendering system.

Figure 5.2. Locations of impact zones on upper guide wall at Gallipolis Lock (Note: Fenders are on left; concrete impacts are on right below white sign)

Micro Measurements Model 2311 strain gage amplifiers provided gage excitation, gain, shunt calibration, and analog prefiltering for the strain, pressure, displacement, and force gages. ERDC-made filters provided analog prefiltering for the remaining 13 acceleration gages. Analog signals for the barge system were interfaced to the PC through a 12-bit digitizer card, and analog signals for the shore system were buffered though a 64-channel multiplex card and then interfaced to the PC through a 12-bit digitizer card. The data acquisition systems were controlled using custom software developed in-house.

All transducers, with the exception of the clevis pin load cells, were calibrated using ERDC calibration practices for resistive shunt calibration. The clevis pins were fielded using the manufacturer sensitivity calibration, as they were not delivered in time to allow pre-experiment calibration at ERDC.

Complete measurement listings of baseline barge, barge with the load bumper, and wall active instrumentation (for both experiments on the concrete and prototype fendering systems) are presented as Tables 5.1, 5.2, and 5.3. Figures 5.3 and 5.4 show the layout and channel number of the instrumentation on the flotilla barges for the baseline and load beam experiments, respectively.

Table 5.1
Baseline Barge Measurements Listing

Measurement Number	Channel Number	Description	Model	Range
S1	1	Strain	EA-06-250RD	20000
S2	2	Strain	EA-06-250RD	20000
S3	3	Strain	EA-06-250RD	20000
S4	4	Strain	EA-06-250RD	20000
S5	5	Strain	EA-06-250RD	20000
S6	6	Strain	EA-06-250RD	20000
S7	7	Strain	EA-06-250BF	20000
S8	8	Strain	EA-06-250BF	20000
S9	9	Strain	EA-06-250BF	20000
S10	10	Strain	EA-06-250BF	20000
S11	11	Strain	EA-06-250BF	20000
S12	12	Strain	EA-06-250BF	20000
S13	13	Strain	EA-06-250BF	20000
S14	14	Strain	EA-06-250BF	20000
S15	15	Strain	EA-06-250BF	20000
S16	16	Strain	EA-06-250BF	20000
S17	17	Strain	EA-06-250BF	20000
P1	18	Pressure	XTM-190	10 psi
P2	19	Pressure	XTM-190	10 psi
F1	20	Lashing load	SPA-50	50 kips
F2	21	Lashing load	SPA-160	160 kips
F3	22	Lashing load	SPA-50	50 kips
F4	23	Lashing load	SPA-50	50 kips
F6	25	Lashing load	SPA-160	160 kips
F7	26	Lashing load	SPA-160	160 kips
F8	27	Lashing load	SPA-160	160 kips
F9	28	Lashing load	SPA-160	160 kips
F10	29	Impact load	SPA-400	400 kips
F11	30	Impact load	SPA-400	400 kips

(Continued)

Table 5.1 (Concluded)

Measurement Number	Channel Number	Description	Model	Range
AX1	31	Acceleration	2310-100	+/- 100g
AY1	32	Acceleration	2310-100	+/- 100g
AZ1	33	Acceleration	2310-100	+/- 100g
AX2	34	Acceleration	2310-100	+/- 100g
AY2	35	Acceleration	2310-100	+/- 100g
AZ2	36	Acceleration	2310-100	+/- 100g
AX3	37	Acceleration	2310-100	+/- 100g
AY3	38	Acceleration	2310-100	+/- 100g
AZ3	39	Acceleration	2310-100	+/- 100g
AX4	40	Acceleration	2310-100	+/- 100g
AY4	41	Acceleration	2310-100	+/- 100g
AX5	42	Acceleration	2310-100	+/- 100g
AY5	43	Acceleration	2310-100	+/- 100g
AX6	44	Acceleration	QA-900	+/- 20g
AY6	45	Acceleration	QA-900	+/- 20g
AX7	46	Acceleration	QA-900	+/- 20g
AY7	47	Acceleration	QA-900	+/- 20g
AX8	48	Acceleration	QA-900	+/- 20g
AY8	49	Acceleration	QA-900	+/- 20g
AX9	50	Acceleration	QA-900	+/- 20g
AY9	51	Acceleration	QA-900	+/- 20g
AX10	52	Acceleration	QA-900	+/- 20g
AY10	53	Acceleration	QA-900	+/- 20g
AX11	54	Acceleration	QA-900	+/- 20g
AY11	55	Acceleration	QA-900	+/- 20g
Trigger signal	56			

Table 5.2
Barge with Load Beam Measurements Listing

Measurement Number	Channel Number	Description	Model	Range
S1	1	Strain	EA-06-250RD	20000
S2	2	Strain	EA-06-250RD	20000
S3	3	Strain	EA-06-250RD	20000
S4	4	Strain	EA-06-250RD	20000
S5	5	Strain	EA-06-250RD	20000
S6	6	Strain	EA-06-250RD	20000
P1	18	Pressure	XTM-190	10 psi
P2	19	Pressure	XTM-190	10 psi
F1	20	Lashing load	SPA-50	50 kips
F2	21	Lashing load	SPA-160	160 kips
F3	22	Lashing load	SPA-50	50 kips
F4	23	Lashing load	SPA-50	50 kips
F6	25	Lashing load	SPA-160	160 kips
F7	26	Lashing load	SPA-160	160 kips
F8	27	Lashing load	SPA-160	160 kips
F9	28	Lashing load	SPA-160	160 kips
F10	29	Impact load	SPA-400	400 kips

(Continued)

Table 5.2 (Concluded)

Measurement Number	Channel Number	Description	Model	Range
F11	30	Impact load	SPA-400	400 kips
AX1	31	Acceleration	2310-100	+/- 100g
AY1	32	Acceleration	2310-100	+/- 100g
AZ1	33	Acceleration	2310-100	+/- 100g
AX2	34	Acceleration	2310-100	+/- 100g
AY2	35	Acceleration	2310-100	+/- 100g
AZ2	36	Acceleration	2310-100	+/- 100g
AX3	37	Acceleration	2310-100	+/- 100g
AY3	38	Acceleration	2310-100	+/- 100g
AZ3	39	Acceleration	2310-100	+/- 100g
AX4	40	Acceleration	2310-10	+/- 10g
AY4	41	Acceleration	2310-10	+/- 10g
AX5	42	Acceleration	2310-10	+/- 10g
AY5	43	Acceleration	2310-10	+/- 10g
AX6	44	Acceleration	QA-900	+/- 20g
AY6	45	Acceleration	QA-900	+/- 20g
AX7	46	Acceleration	QA-900	+/- 20g
AY7	47	Acceleration	QA-900	+/- 20g
AX8	48	Acceleration	QA-900	+/- 20g
AY8	49	Acceleration	QA-900	+/- 20g
AX9	50	Acceleration	QA-900	+/- 20g
AY9	51	Acceleration	QA-900	+/- 20g
AX10	52	Acceleration	QA-900	+/- 20g
AY10	53	Acceleration	QA-900	+/- 20g
AX11	54	Acceleration	QA-900	+/- 20g
AY11	55	Acceleration	QA-900	+/- 20g
Trigger signal	56			

Table 5.3
Lock Wall Measurements Listing

Measurement Number	Channel Number	Description	Model	Range
ACC-L1	1	Acceleration	QA-1100	+/- 15 g
ACC-L2	2	Acceleration	QA-1100	+/- 25 g
ACC-L3	3	Acceleration	QA-1100	+/- 10 g
ACC-L4	4	Acceleration	QA-1100	+/- 10 g
D-1 (TR)	5	Deflection	PT101-0040-11-1110	40 in.
D-2 (TL)	6	Deflection	PT101-0040-11-1110	40 in.
D-3 (BR)	7	Deflection	PT101-0040-11-1110	40 in.
D-4 (ML)	8	Deflection	PT101-0040-11-1110	40 in.
D-5 (MR)	9	Deflection	PT101-0040-11-1110	40 in.
D-5 (BL)	10	Deflection	PT101-0040-11-1110	40 in.
Trigger	11	Trigger		
Accel-X	13	Acceleration	2430-050	+/- 50 g
Accel-Y	14	Acceleration	2430-050	+/- 50 g

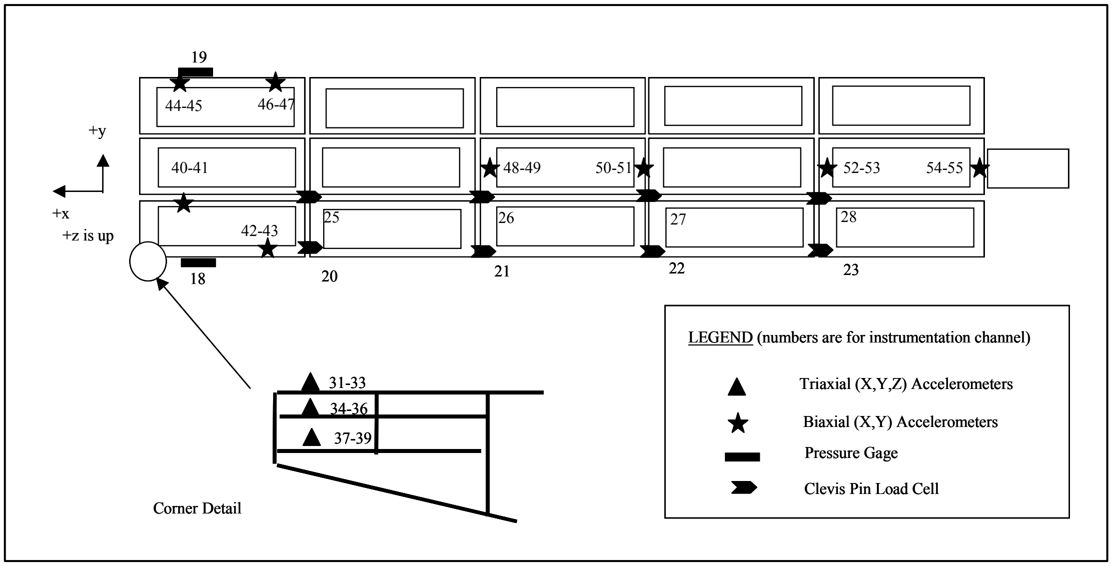


Figure 5.3. Instrumentation channels for baseline experiments

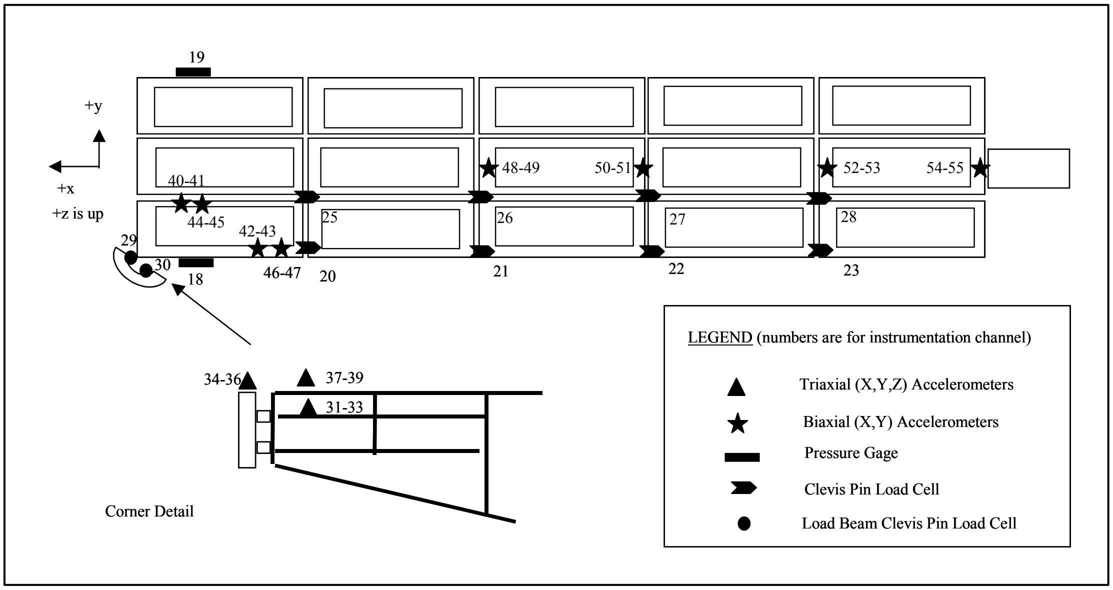


Figure 5.4. Instrumentation channels for load bumper experiments

5.3 Barge Instrumentation

5.3.1 Accelerometers

Triaxial accelerometer configurations were placed at three locations at the impact zone. For the baseline corner barge, all three packages were mounted on a vertical center line: one on the deck, and the other two on gussets below the decking for the baseline barge. For the barge with the load beam, one triaxial accelerometer was mounted on the impact bumper, one on the deck of the barge, and the third on the gusset below the decking for the impact barge (Figure 5.5). These acceleration measurements were made using Model 2210-100 capacitive accelerometers manufactured by Silicon Designs, Inc.

Biaxial accelerometer configurations were placed at two locations on the impact barge and at two locations on three other barges. Figure 5.6 shows the typical installation of these biaxial gages. All gages were mounted with the same orientation. The acceleration measurements on the impact barge were made using Model 2210-010 capacitive accelerometers manufactured by Silicon Designs, Inc. The acceleration measurements at the other locations on the flotilla were made using Model QA-900 quartz flexure accelerometers manufactured by Sunstrand Data Control, Inc. After baseline testing, two of the biaxial configurations were moved to the impact barge from one of the other barges. These were placed beside the two biaxial configurations on the impact barge. Locations of these biaxial devices are indicated with star symbols in Figures 5.3 and 5.4.

5.3.2 Strain gages

Two strain gage rosettes were installed on the barge decking near the impact corner. These gages were located to the port side of the bits located near the barge corner and were to measure strain components in the x- and y-axes and 45 deg between x and y. Single-axis gages were placed on the coaming rails near the midpoint of the impact corner barge to measure effective bending strain on the barge during impact. A series of nine locations underdeck in the impact corner were instrumented with single-axis strain gages. The general location of the strain gages is shown in Figure 5.7, and their location underdeck is shown in Figure 5.8. All strain gages were bonded to the decking using Measurements Group M-Bond 200 epoxy after the barge metal was cleaned with a grinder. Bridge completion networks were used adjacent to each strain gage to provide temperature compensation.

5.3.3 Clevis pin load beam

The primary purpose of the clevis pin load beam was to measure the actual impact forces normal to the wall during a controlled impact. The target design for the load beam required an instrumentation device that could handle normal loads up to 1,200 kips along with the corresponding shear loads due to the friction of the wall. Members of the ERDC Barge Impact Team discussed many design concepts, including designs for both the lock wall and the barge corner. Each proposal had its benefits and drawbacks. The final design that was selected, the clevis pin load beam, was the best overall design concept given a tight schedule for both construction time and funding.

Figure 5.5. Accelerometers on gussets under deck in impact corner

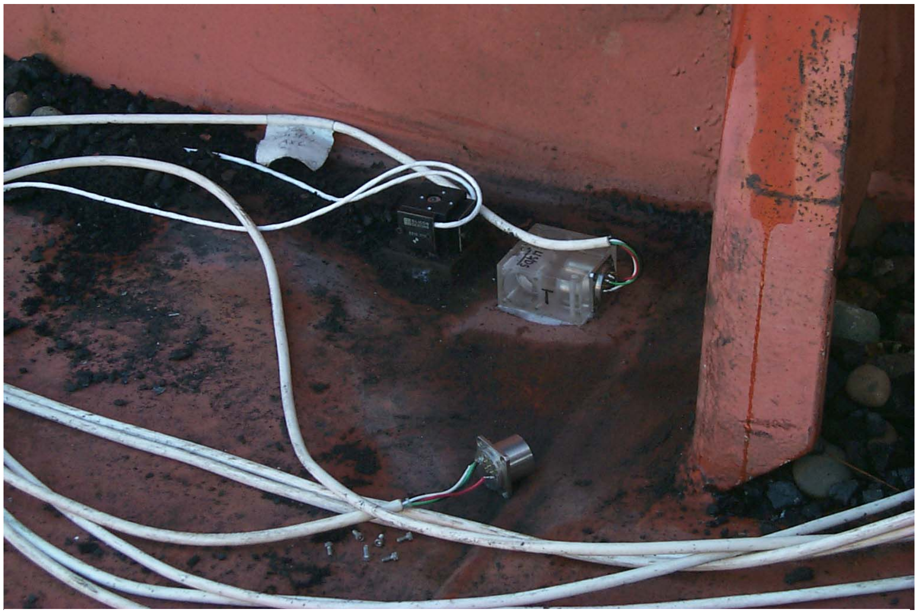


Figure 5.6. Biaxial accelerometer on the barge deck

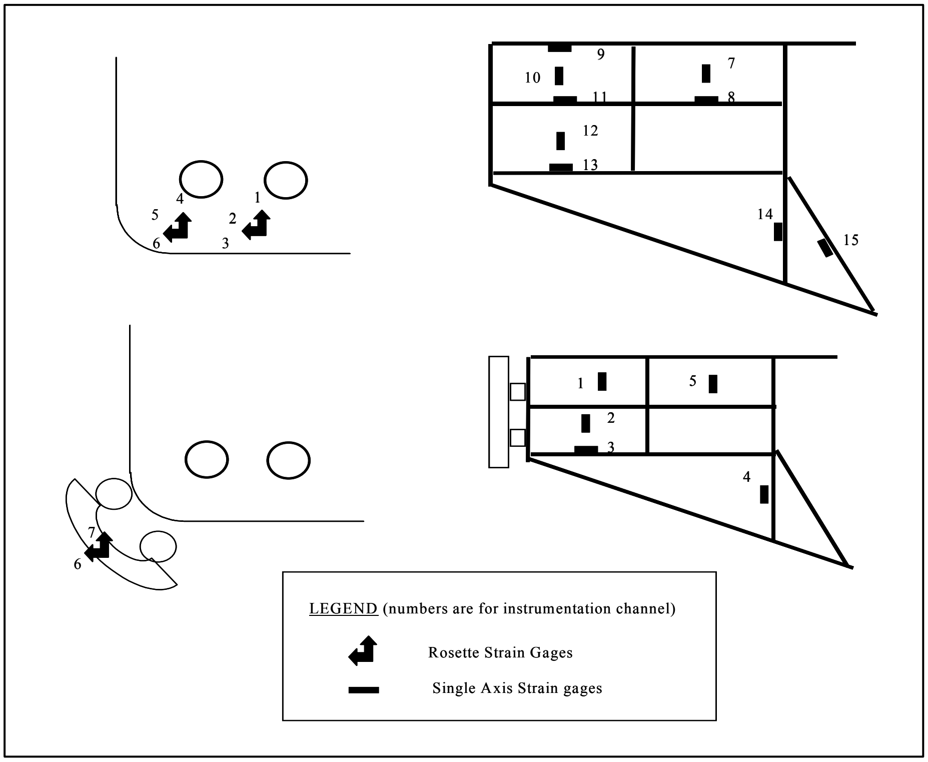


Figure 5.7. Instrumentation channels and locations for strain gages during baseline and load beam experiments

Figure 5.8. Layout of strain gages under deck for baseline experiments (Note: Yellow tape covers the strain gage locations)

The final design for the load beam was the most efficient in terms of both cost and availability of materials, as well as time to construct. The load beam was machined directly at ERDC machine shops, with the steel plates being supplied from and cut by a local steel supplier. The clevis pin load beam consisted of four basic sections:

a. *Load beam*. This is a 9-in.-wide curved steel beam that was cut from a 5-in.-thick steel plate. The steel section was cut to an inner radius of 63.6 in. and an outer radius of 72.6 in. This gave an outer length of 43.6 in. and an inner length of 38.2 in. Holes in the beam were cut for the clevis pins (diameter 6.018 in. with ±0.005 tolerance.

b. *Clevis mounts*. The clevis mounts that hold the load cells were cut from steel plate. This mount consists of three plates: horizontal top and bottom 3-in.-thick plates to hold the clevis pin and a vertical 2-in.-thick plate to attach to the barge. Similar to the load beam, the horizontal plates had 6.018-in.-diam holes cut through them to hold the load cells. This would attach to the barge-mounting plate below, with 1-in. high-strength bolts.

c. *Barge mounting plate*. The mounting plate to the barge was constructed of a 2-in.-thick steel plate. The plate was cut on the back side to a radius of 61.2 in. to closely match that of the curved impact corner. This piece was welded onto the barge hull prior to the experiments.

d. *Clevis pin load cells*. These cells were Strainsert SPA-400 type, which had the capacity to carry 400 kips of impact. The cells had a 50 percent over-range capacity, allowing for a maximum total load of 1,200 kips.

The load beam was calibrated using a 2 million-pound load ram at ERDC. Calibration was taken at specific increments across the load beam and at varying load increments up to 1,000 kips. This calibration would verify consistent readings from the ram to the load cells and assist with any corrections that might be needed to field data. Figures 5.9 and 5.10 show the load beam in the testing facility at ERDC and after mounting.

One of the compromises that had to be made with the design was that both clevis supports had to be fixed to the barge through welds. This made the beam into a fixed-fixed beam, which made it an indeterminate structure. Another compromise involved the clevis pin load cells ordered from Strainsert Corporation, which measured only the normal component of the impact load and not the shear component. This situation occurred as a result of both time and cost constraints, since these types of load cell are not typically found off-the-shelf. Unfortunately, both of these compromises created difficulty in postprocessing of the clevis pin load data.

In addition to the clevis pin load cells, an alternative force-measuring technique was included as a parallel load-measuring effort. Polyvinylidene fluoride (PVDF) thin-film piezoelectric stress gages were developed into flat packs at ERDC and attached to the front of the load beam through a sandwich of

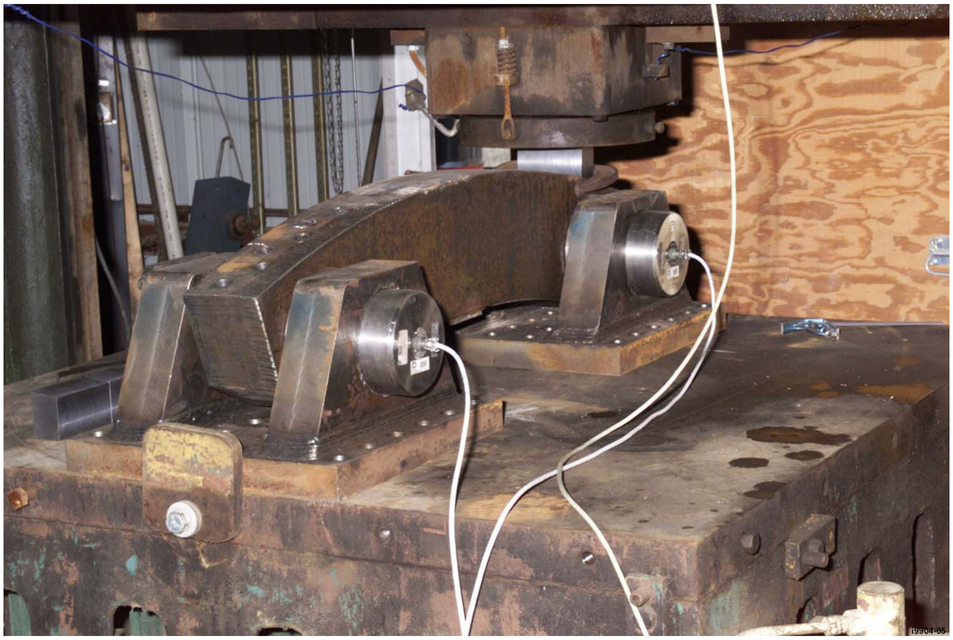


Figure 5.9. Calibration of load beam at ERDC

Figure 5.10. Clevis beam load beam (Note: Barge mounting plate is against barge; next is the vertical clevis mount, followed by horizontal clevis mounts. The load beam is under the clevis and runs to the left. The instrumented clevis pin was not inserted at this time to avoid damage during installation of load beam)

plates. Laboratory research and testing were conducted prior to the experiments using dynamic loading on the materials and yielded good results. However, due to the quality of the PVDF material and the required shear configuration for the cover plates and attached bolts, these devices were not used in the final experiments. However, if this type of material is configured and calibrated correctly it may supply another legitimate method of impact load measuring if attached to the surface of a lock wall. Figure 5.11 shows the installed clevis pin load beam from the side and top views. Figure 5.12 shows the load beam impacting the lock wall.

5.3.4 Lashing instrumentation

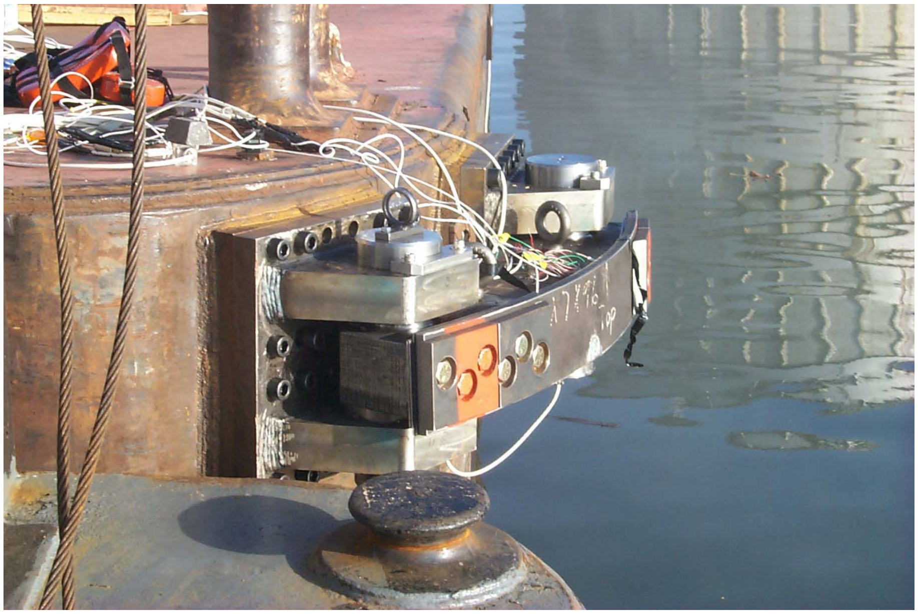
The steel cable lashings that connect the barges together were instrumented with clevis pin load cells to measure the change in force response during an impact. The lashing system can be represented as a spring or an additional degree of freedom within the barge system. The lashing system is composed of different layering. Typically, three layers of lashing are found between the strings on inland waterway tows and a single layer is found connecting the outer strings. For between strings, the layers are called fore/aft wires, scissor wires, and “breast” wires. Sometimes these inner systems are broken down into two terms, towing or backing wires. For the port and starboard strings the layers are called fore/aft wires. Each of these layers performs different functions during the transit and locking of the flotilla. The typical layout of each layer of the flotilla is shown in Figures 5.13-5.16. Figure 5.17 and 5.18 show the typical layout of the towing/backing wires and port wire, respectively.

The layouts of the lashings for the full-scale experiments were very similar to the layers described above, with some variation due to the incorporation of the instrumented cables. Most of the instrumented clevis pin load cells were “cut” into the first or second part (a segment of wire between the barges) of the breast lashings depending upon their location within the flotilla. The lashings used for the experiments were 35 ft long, which is typical for inland tows.

Two lashing types were used for the full-scale experiment. The lashings used on the port side were 1-in.-diam wire. The ultimate tensile strength of that wire was rated at 90 kips. The inner lashings were 1-1/4-in. wire that was rated at an ultimate tensile strength of 120 kips. The instrumented lashings were positioned in eight locations on the barge flotilla, as shown in Figure 5.19. Details of the lashing instrumentation are given in Table 5.4. An example of the instrumented lashings with the clevis pin load cells cut into a lashing port is shown as Figure 5.20.

5.3.5 Water pressure sensors

Two piezoresistive pressure gages, Model XTM-190 manufactured by Kulite Semiconductor Products, Inc., were mounted to the right side of the lead barge. These gages were mounted in an aluminum disc glued to a magnet, which was then attached magnetically to the barge hull. The pressure gages, designated as P1 and P2, were located at a depth of 32.5 in. below the waterline and at 15 and 23 ft



a. Side view

b. Top view

Figure 5.11. Clevis pin load beam

Figure 5.12. Load beam impacting guide wall

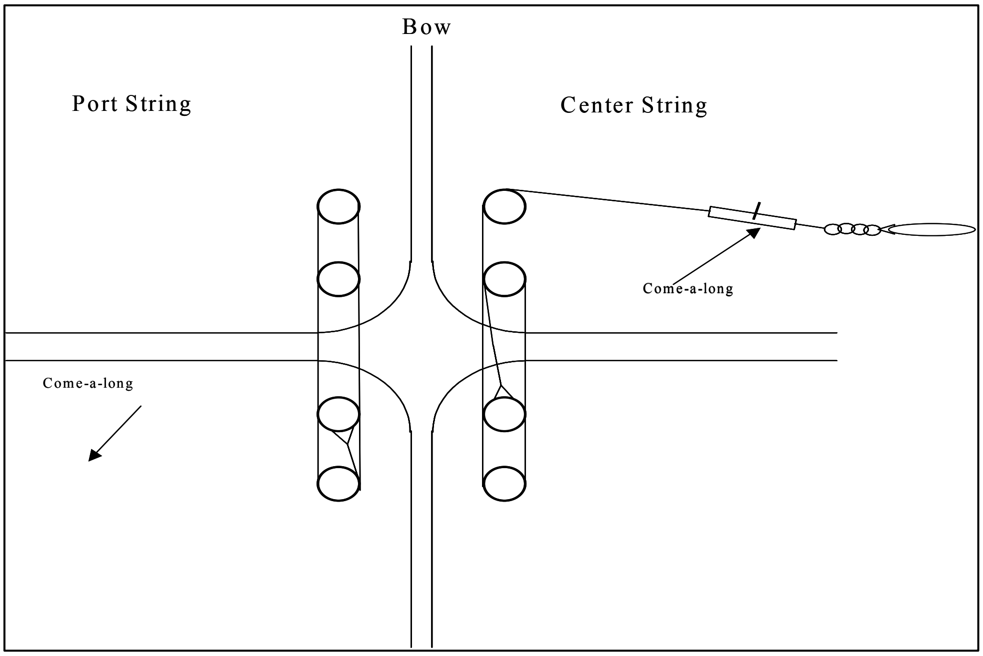


Figure 5.13. Fore/aft wires between port and center string

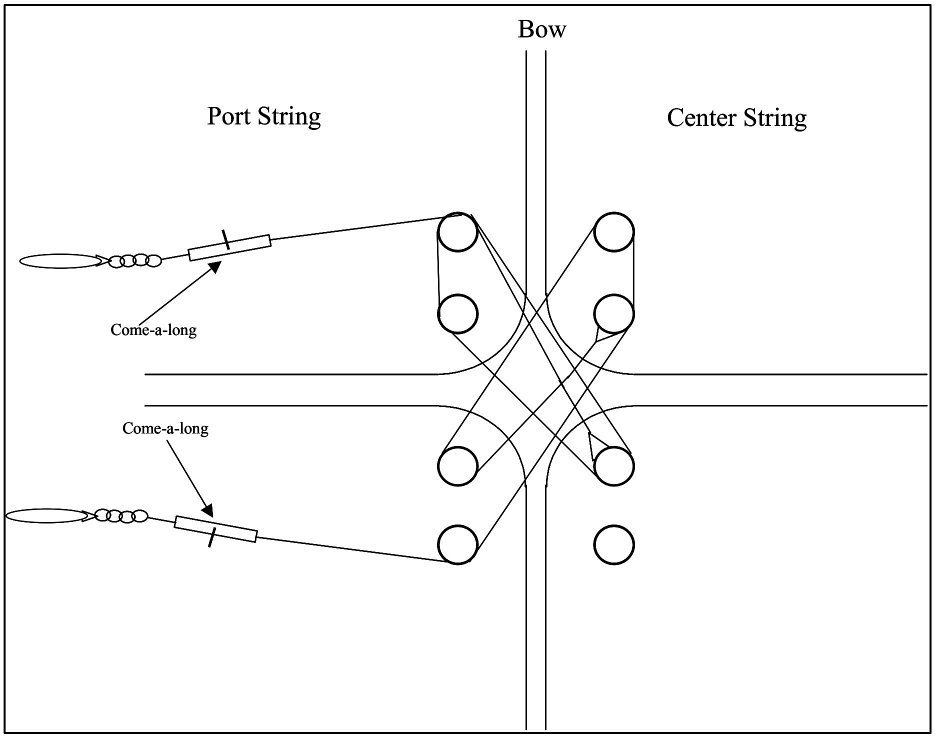


Figure 5.14. Scissor wires port and center string

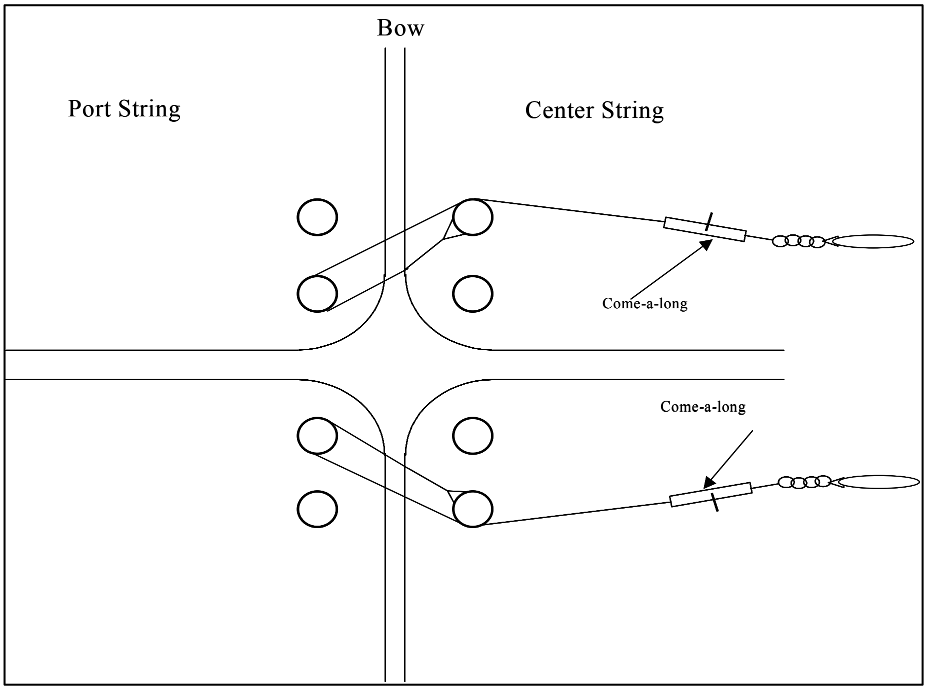


Figure 5.15. Breast wires between port and center string

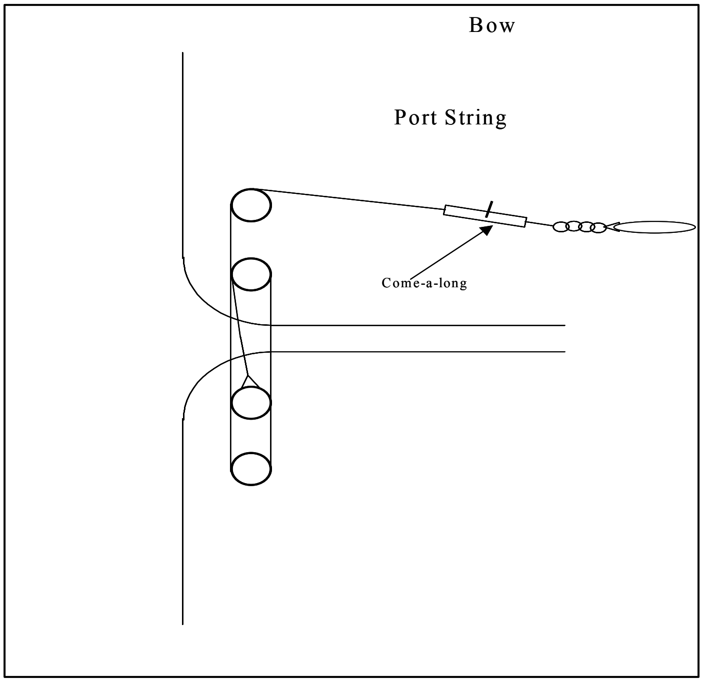


Figure 5.16. Fore/aft wires on port barge strings

Figure 5.17. Typical towing/backing layout for full-scale experiments

Figure 5.18. Typical port lashing with clevis load cell

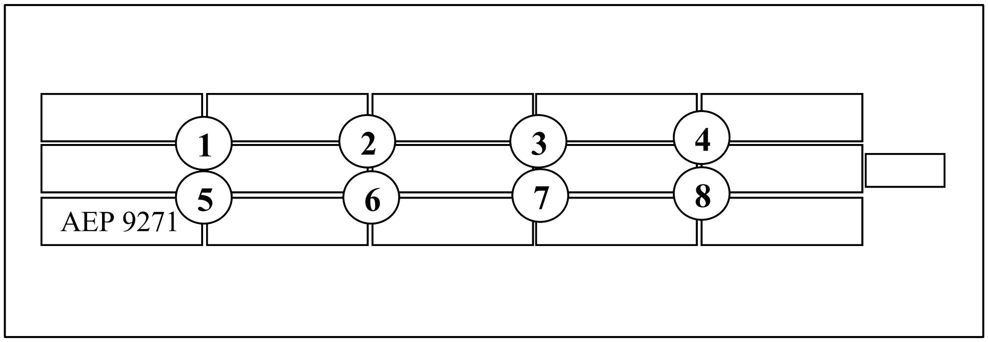


Figure 5.19. Location of instrumented lashings

Table 5.4
Lashing Load Cells

Position (Figure 5-19)	Type	Load Cell No.	Load Capacity of Cell (kips)	Instrumentation Channel No.
1	Towing	014099-1	160	25
2	Towing	014099-3	160	26
3	Backing	014099-5	160	27
4	Towing	014099-2	160	28
5	Fore/aft	013654-1	50	20
6	Fore/aft	014099-4	160	21
7	Fore/aft	013671-1	50	22
8	Fore/aft	013654-3	50	23

Figure 5.20. Clevis pin load cells in lashings

back from the impact corner. The purpose of these devices was to capture a rise/fall in water pressure due to the confinement effects of the wall on the side hull of the barge before, during, and after the impact. The gages were protected from impacts to the lock wall using rubber tires mounted to the barge side.

5.4 Lock Wall Instrumentation

The instrumentation on the lock wall consisted of devices on the top of the lock wall at both impact locations, the concrete wall and prototype fenders, as well as those mounted directly on the fenders. The instrumentation used for both locations is shown in Figure 5.21.

Accelerometer mounts were attached to the top of the lock wall at eight locations (four at each impact location), as indicated in Figure 5.22. Two accelerometers were placed on the impact monolith, and the others were mounted on the two adjacent monoliths. This was done to examine if there were any differences in acceleration between the monoliths during an impact. The accelerometers were Model QA-1100 quartz flexure accelerometers manufactured by Sunstrand Data Control, Inc. The range of these accelerometers was from ±10 to ±25 g's. These are extremely linear, high-output devices that are well suited for these measurements. The mounts were glued to the top of the lock wall with 5-Minute Epoxy, as shown in Figure 5.22.

On the prototype fendering system, position transducers (Model PT101-0040-111-1110) manufactured by Celesco Transducer Products, Inc., were bolted to a mounting plate that was then welded onto the fendering system. These transducers, commonly called "yo-yos," were used to measure the deflection of

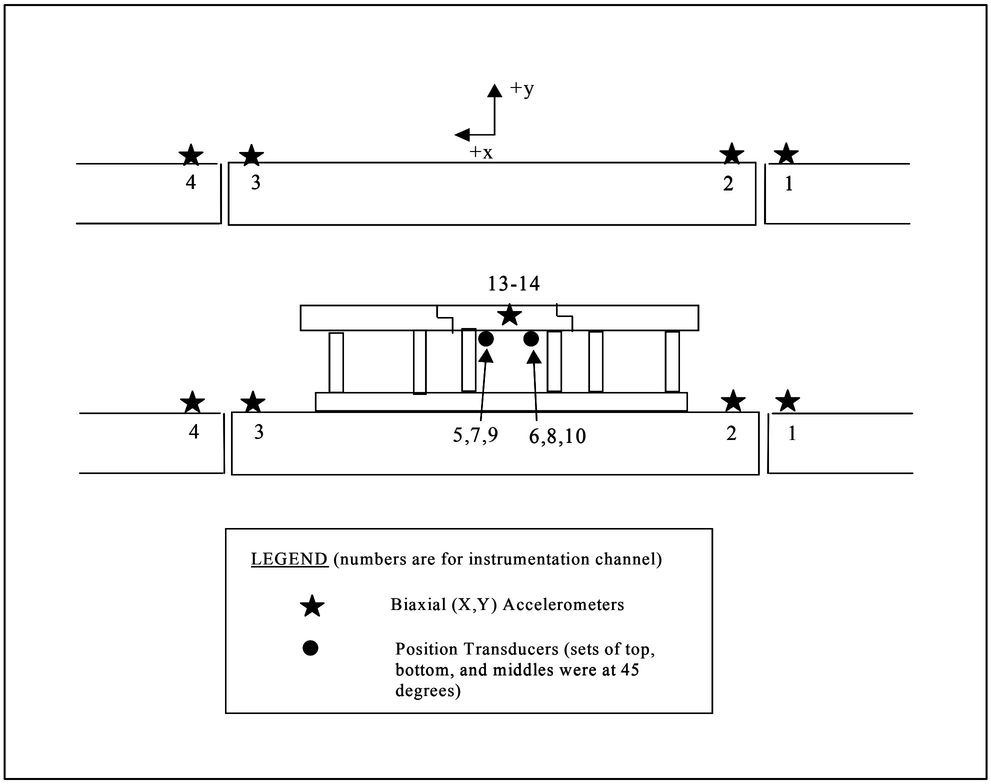


Figure 5.21. Location of instrumentation on lock wall and prototype fenders

Figure 5.22. Installation of accelerometers on lock wall

the fenders. The position transducers used for these experiments had a range of 40 in. Yo-yos were installed at the top and bottom of the fenders and at a 45-deg angle at the midpoint.

Figure 5.23 shows the position transducers before the fenders were installed on the lock wall. A triaxial accelerometer was also bolted to the prototype fender. The capacitive accelerometer used for the experiment was a Silicon Design, Inc., Model 2430-050. The range for the accelerometer was ±50 g's.

Figure 5.23. Position transducers on the prototype fenders

5.5 Differential Global Positioning System

The DGPS equipment included three Trimble 4000SSI dual-frequency receivers that were mounted to the tow to measure the angle, speed, and point of impact on the guide wall. Two receivers were placed on the impact corner barge, and the third was located near the center of the flotilla. The DGPS antennas were mounted on the barges using magnetic mounts, as shown in Figure 5.24. The antennas were positioned to minimize interference and provide the best possible satellite reception.

A real-time GPS system was used at the helm on the towboat to assist the operator in attaining the desired velocities prior to impact. A 4000SSI receiver was placed on the top of the Gallipolis Dam to record raw data for post-processing. A static survey was conducted and postprocessed against the Continuous Operating Reference Station at Huntington, WV, to obtain an accurate position for the base unit and the lock wall.

Figure 5.24. DGPS antennas on flotilla

The DGPS units recorded raw data at intervals of 1 sec. The data from the mobile DGPS units was postprocessed to obtain accurate differential positions of the units during the experiments. The locations of the mobile DGPS units, instrumentation gages, and geometry of the barges were measured using a Topcon Total Station with tilt compensation.

5.6 High-Speed Cameras and Videotape Equipment

A high-speed camera and video cameras were used to further document each impact event. The video and high-speed cameras were very valuable in capturing the barge/wall interaction during impact. The high-speed camera used for the experiments shot at 100 frames per second to capture any deformation of the barge into the lock wall. This high-speed camera and one video camera (used for redundancy of image) were mounted on a stand that was 4 ft off the top of the lock wall. This stand permitted the rotation of the cameras to overhang the lock wall by about 4 ft, such that it would produce a relatively “unwarped” view of the impact zone set below on the lock wall. Figure 5.25 shows the mount with the high-speed and video cameras that overhung the lock walls.

Figure 5.25. High-speed camera and video cameras on and extended over lock wall

6 Prototype Fendering System

6.1 Introduction

A prototype fendering system was developed and built for the full-scale barge impact experiments at R.C. Byrd Lock and Dam (Old Gallipolis Lock and Dam). This was a collaborative effort undertaken by the ERDC, Vicksburg, MS, and Svedala-Trellex of Keokuk, IA. The goal of the prototype fendering system was to examine the potential for using such a device for absorbing impact energy from a fully ballasted tow at navigation approach walls. Fendering systems have not yet been used at any Corps navigation facility. With additional development, it is hoped that this type of system could be easily implemented into innovative navigation projects, permitting the potential savings of millions of dollars in structure costs. The prototype fendering system at Old Gallipolis Lock is shown in Figure 6.1.

Figure 6.1. As-built prototype fendering system on upper guide wall at Gallipolis Lock and Dam

6.2 Design of Prototype System

The design concept for the prototype fendering system was developed around similar concepts used for the design of fendering system for docks and ferry facilities. However, the difference with the navigation fenders is that they need to permit a tow to land at higher speeds and angles than traditional harbor fender designs. In addition, the design had to consider the ability of a tow to rub continuously along the surface, change the direction of the energy from the tow, and react to a motion unfamiliar to dock fendering systems.

The prototype fenders used for these experiments were of traditional fender element design (by Svedala-Trellex), in conjunction with a steel impact box that was faced with ultra-high molecular weight plastic. This UHMW product can be considered frictionless and is nearly incompressible. This surface permits the tow to slide along the wall without slowing down or hanging up on the wall. In addition, composite impact boxes of steel and concrete were built. However, due to the time limitations, these were not used during the experiments. Figures 6.2 and 6.3 show the as-built designs for the prototype fendering segments.

Figure 6.2. Prototype fendering segment—side view

The fender system was mounted to the upper approach wall at the Old Gallipolis Lock and Dam using a steel plate guiding system that was backed with rubber sheathing to transfer the impact loads over the entire wall. The mounting guide system was attached to the wall using 1-1/2- by 14-in. high-strength anchor bolts that were epoxied into patterned holes in the lock wall. The entire system was delivered by semi-trailers in separate pieces and assembled on the floating plant within the old lock chamber. The installation of the entire system on the lock wall at Gallipolis was accomplished using a spud barge that housed a 90-ton truck crane. Figure 6.4 shows the insertion of a panel into the wall guide system.

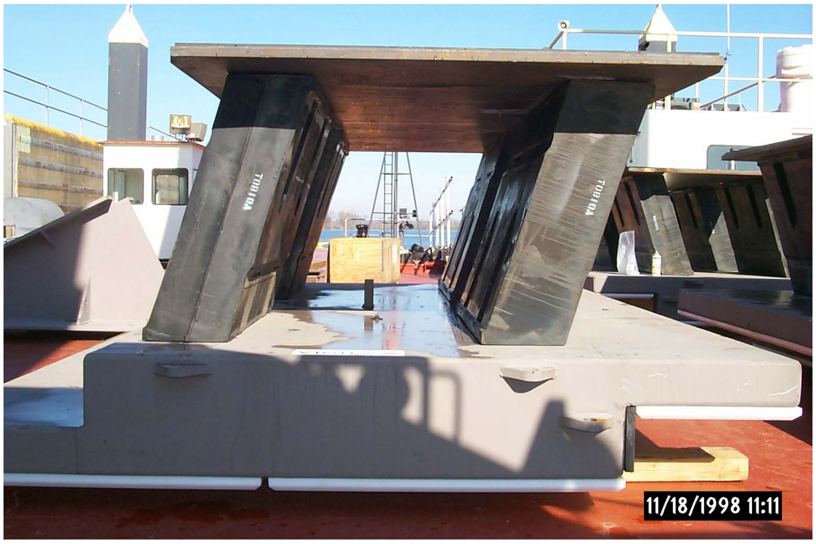


Figure 6.3. Prototype fenders—top view

Figure 6.4. Insertion of middle prototype panel into wall fendering system

Currently, this system is under patent review by the Office of Patents in Washington, DC. It is being patented by both the U.S. Army Corps of Engineers and Svedala, for both the application and concepts as well as design of the prototype fendering system.

6.3 Experiments

Fourteen experiments were accomplished on the prototype fendering system during the experiments at R.C. Byrd Lock and Dam. The fendering system was instrumented with accelerometers to measure impact shocks and displacements and with deflection measurement devices at more than seven points on the fendering system. These data are being processed and reviewed at the ERDC. Nine experiments were performed using both the baseline barges to examine the behavior of the prototype system compared with similar impacts on the mass concrete lock wall. Five experiments were conducted using the clevis load beam to measure actual impact loads normal to the fenders. Figure 5.23 shows the deflection instrumentation on the panel segments.

The impact velocities ranged from 0.53 to 2.05 mph with the impact angle for the barge between 5.5 and 20 deg. The experiment number, impact location on the fender system (three panels were used), and impact data are shown in Table 6.1. Figure 6.5 shows the typical deflection of the prototype system during the experiments.

Table 6.1
Experiments Performed on Prototype Fendering System

Experiment No.	Impact Location	Velocity (mph)	Impact Angle (deg)
13	Middle panel	0.53	5.5
14	First panel	1.1	10.25
15	First panel	1.1	13.5
16	Second panel	1.55	13
17	Second panel	1.6	15
18	Second panel	1.9	16
19	Second panel	2.05	20
20	First panel	1.5	7
21	First panel	0.75	12.5
32	First panel	0.82	12.25
33	First panel	1.5	17.5
34	First panel	1.95	19.25
35	First panel	1.05	8.75
36	First panel	1.6	15.25

6.4 Conclusions

Initial data from the full-scale experiments at R.C. Byrd Lock and Dam have indicated that the prototype fendering system developed for the experiments shows very high potential for greatly reducing the impact forces from tows at navigation projects. With continued development toward innovative structures, the use of such a system could lead to significant reduction in the overall costs of design and construction of navigation projects. Corps navigation projects in the Louisville, Nashville, St. Paul, and New Orleans Districts are examining the

a. Side view

12/2/1998

b. Top view

Figure 6.5. Typical deflections of fender system during impact

use of such a fendering system for approach walls at their navigation facilities. Potential innovations for protection systems of bullnoses are also under development. The only potential unknowns for using such a fendering system on the inland waterways center on maintenance and repairability issues. These problems are being addressed by both industry and the Corps of Engineers.

7 Observations from Full-Scale Impact Experiments

7.1 Preliminary Results

Forty-four full-scale barge impact experiments were conducted on a lock wall at Robert C. Byrd Lock and Dam (Old Gallipolis Lock) in Gallipolis Ferry, WV. The primary goal of these experiments was to measure the actual impact forces normal to the wall using a load-measuring device. Other objectives of these experiments were to obtain and measure the baseline response of an inland waterway barge, quantify a MDOF system during impact, and investigate the use of energy-absorbing fenders. All these goals were successfully met at the experiments during the 3-day test period that was available.

The impact experiments were successfully conducted on the rigid concrete upper guide wall at angles of impact ranging from 5 to 25 deg with velocities of 0.5 to 3 ft per second. Of the 44 experiments, 21 were baseline impacts (12 on the lock wall and 9 against a prototype fendering system mounted on the lock wall) using the baseline barge. For the remaining 23 impact tests (18 on the lock wall and 5 on the prototype fendering system), the corner barge was replaced with one fitted with the load-measuring bumper. A summary chart is given below.

Total No. of Full-Scale Impact Experiments = 44
Baseline experiments: 21
12 baseline on concrete
9 baseline on fendering system
Load Beam Experiments: 23
18 load measurement on concrete
5 load measurement on fendering systems

Tables 7.1 - 7.5 show the ***unprocessed*** speed and impact angle for each set of experiments. Figures 7.1 - 7.4 show the plots of the matrices for ***unprocessed*** speed and angle for each of the experiments.

Table 7.1
Baseline Experiments, Impact Angles and Velocities

Experiment No.	Velocity at Impact (ft/sec)	Angle at Impact (deg)
1	0.73	10
2	1.32	5.5
3	1.61	12
4	2.32	8
6	2.29	21
7	2.79	13
8	3.15	10.5
9	1.76	15
10	3.59	11.5
11	4.11	9
12	2.51	14.5

Table 7.2
Baseline Fender Experiments, Impact Angles and Velocities

Experiment No.	Velocity at Impact (ft/sec)	Angle at Impact (deg)
13	0.78	5.5
14	1.61	10.25
15	1.61	13.5
16	2.27	13
17	2.35	15
18	2.79	16
19	3.01	20
20	2.20	7
21	1.10	12.5

Table 7.3
Load Beam Experiments, Impact Angles and Velocities

Experiment No.	Velocity at Impact (ft/sec)	Angle at Impact
22	0.88	10
23	0.81	15.5
24	1.10	18
25	2.20	16.25
26	1.03	23.75
27	2.20	8
28	2.35	12.5
29	2.20	15
30	2.35	15
31	1.61	13.25
37	1.95	12.5
38	1.83	14.25
39	1.61	17.25
40	1.91	20.25
41	2.86	11.5
42	1.83	18.5
43	0.88	25
44	1.22	23

Table 7.4
Baseline Fenders Experiments, Impact Angles and Velocities

Experiment No.	Velocity at Impact (ft/sec)	Angle at Impact
32	1.20	12.25
33	2.20	17.5
34	2.86	19.25
35	1.54	8.75
36	2.35	15.25

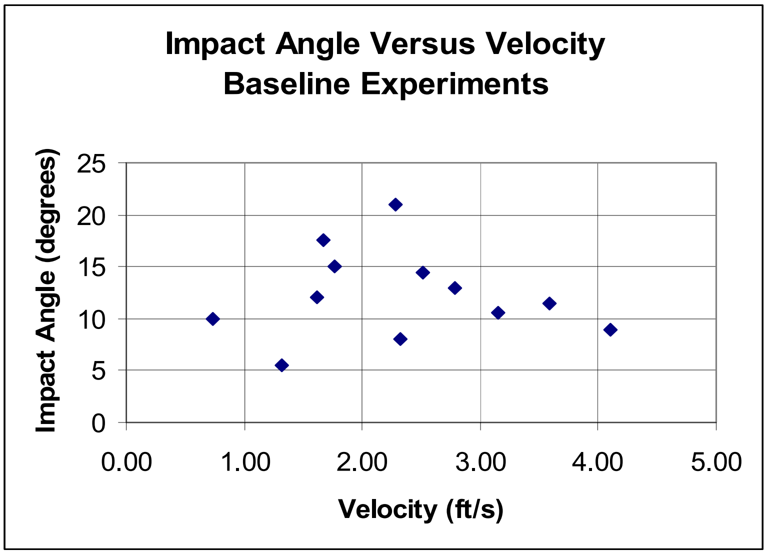


Figure 7.1. Impact angle versus velocity–baseline experiments

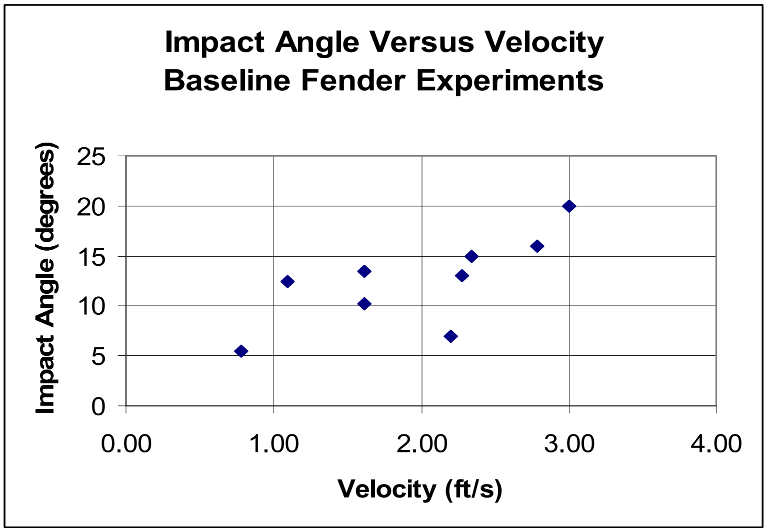


Figure 7.2. Impact angle versus velocity–baseline fender experiments

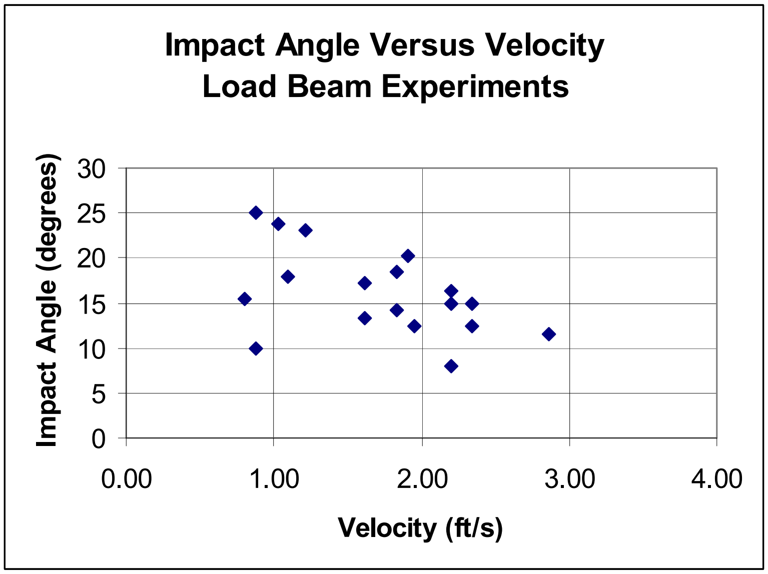


Figure 7.3. Impact angle versus velocity–load beam experiments

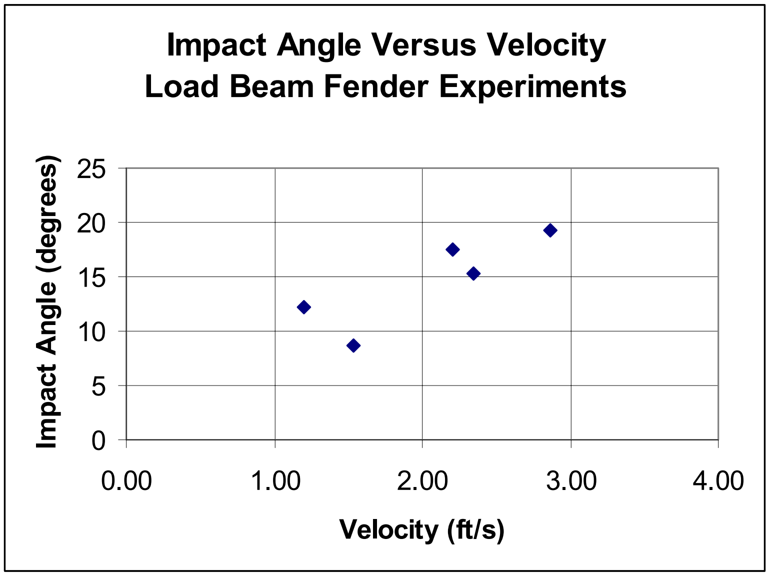


Figure 7.4. Impact angle versus velocity–load beam fender experiments

7.2 Observations

The following observations are made from the results of these full-scale experiments:

- Barge corners do not permanently deform during controlled impacts into a rigid concrete lock wall. This was directly indicated by the strain gages on the impact corner barge, the videotape/high-speed camera images that were captured, and postevent examination of the barges.
- The ETL 338 method appears to be very conservative and will most likely overpredict the impact force of a controlled tow at the speeds and angles captured in the matrices. This observation is based on preliminary interpretation of the clevis pin load beam data and is further supported in the detailed analysis of the load-beam data found in Arroyo, Ebeling, and Barker (2003).
- The barge lashings do contribute to energy transfer in barges, depending upon impact speed and angle. This information can be seen directly in the data from the clevis pin load cells that were spliced into the lashings.

The following results from the full-scale experiments are documented:

- Actual measurements of impact loads under controlled approaches of a fully ballasted tow.
- Collection of data sufficient to calibrate future numerical models.
- Development of a better understanding of the physics of a MDOF barge system before, during, and after a controlled impact into a lock wall.
- Invalidation of the TDOF system model found in ETL 338.

The following observations and results from the testing of the prototype fendering system were noted:

- Lock wall fendering systems show a very high potential for use on inland waterway projects. These experiments demonstrated their durability and capabilities to absorb barge-impact energy.
- The prototype fendering system has a significant force reduction capability, based on preliminary results of reducing impact forces during controlled impacts. The fenders used for this system were considered relatively stiff and rigid due to the unexpected uncertainties of the impact load. If this system were “softened” by 80 to 90 percent more, a significant additional load could easily be absorbed and final velocities reduced to near zero.

- The prototype fendering system can be fabricated into existing and new navigation structures. This was directly shown by the system developed specifically for these experiments.

- Fendering systems are a low-cost alternative compared with increasing the width of an approach wall. Potential applications would be upper guide/guard walls, bullnoses, and protection cells.

- Questions will arise on both maintenance costs and durability over time. These aspects of the design can be addressed with minimal research and development efforts.

The copious amounts of impact data that were collected during these experiments can be used for calibration of numerical models. However, for the purposes of this report and since the data trends are important in understanding how and if the instrumentation worked, two appendixes are published with this report to include representative examples of raw data plots for the instrumentation.

Appendix A presents plots for the barge instrumentation, and Appendix B contains the plots for the lock wall instrumentation.

Caveat to the reader: This data in Appendixes A and B has not been intepreted. Any further interpretation of the data may be left to possible misinterpretation by those unfamiliar with how the data was recorded and the type of instrumentation that was used to collect the data.

8 Conclusions and Recommendations

The full-scale experiments at Robert C. Byrd Lock and Dam are valuable in defining and quantifying barge impact forces as well as documenting the barge-wall and barge-barge interactions during impacts. This information is valuable for the validation/invalidation of the existing TDOF model defined in ETL 338, as well as assisting with further numerical modeling efforts to better define the true MDOF barge system. The final results from these experiments should better assist the Corps with the design of innovative structures for barge impact loads.

The following recommendations are made regarding some modifications for any future barge or ship impact experiments. First, the more experiments the better. The anticipated experiment matrix for these tests was established for nearly 90 experiments planned over a 5-day period (including barge change out). However, for these experiments, the availability of the tow for testing was only 3 days (including corner barge change out). That greatly limited the number of experiments that could be performed.

Second, plan the experiments for a warm (not too hot) but dry part of the year with longer daylight hours. Since these experiments were in early December, the length of a day was much shorter than desired. This created problems due to darkness in the early morning and late evening hours for both instrumentation and tow staff assistance. This darkness, even with halogen lighting, affected the speed of mobilization, change out of barges, and demobilization of the flotilla. Luckily, the weather held during these experiments. The experiments were performed without any precipitation and with daily highs in the 60’s (ºF). This was fortunate for December weather and could have been much worse.

Third, a majority of the instrumentation performed extremely well under these controlled impact load conditions. Most importantly, the clevis pin load beam was highly effective and provided valuable insight and data for actual barge impact loads. However, several improvements should be integrated into future designs of the load beam. These include additional capabilities to measure the shear load in the clevis pins, mounting the rear clevis as a free-end condition which would remove the indeterminacy of the beam, and enlarging and smoothing the rub contact surface to be similar to the face of a barge corner.

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Arroyo, J. R., Ebeling, R. M., and Barker, B. C. (2003). "Analysis of impact loads from full-scale, low-velocity, controlled barge impact experiments," Technical Report ERDC/ITL TR-03-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

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Patev, R. C. (1999). "Full-scale barge impact experiments," Transportation Research Board Circular No. 491, Inland Waterway Technical Studies, National Transportation Research Board/National Research Council, Washington, DC.

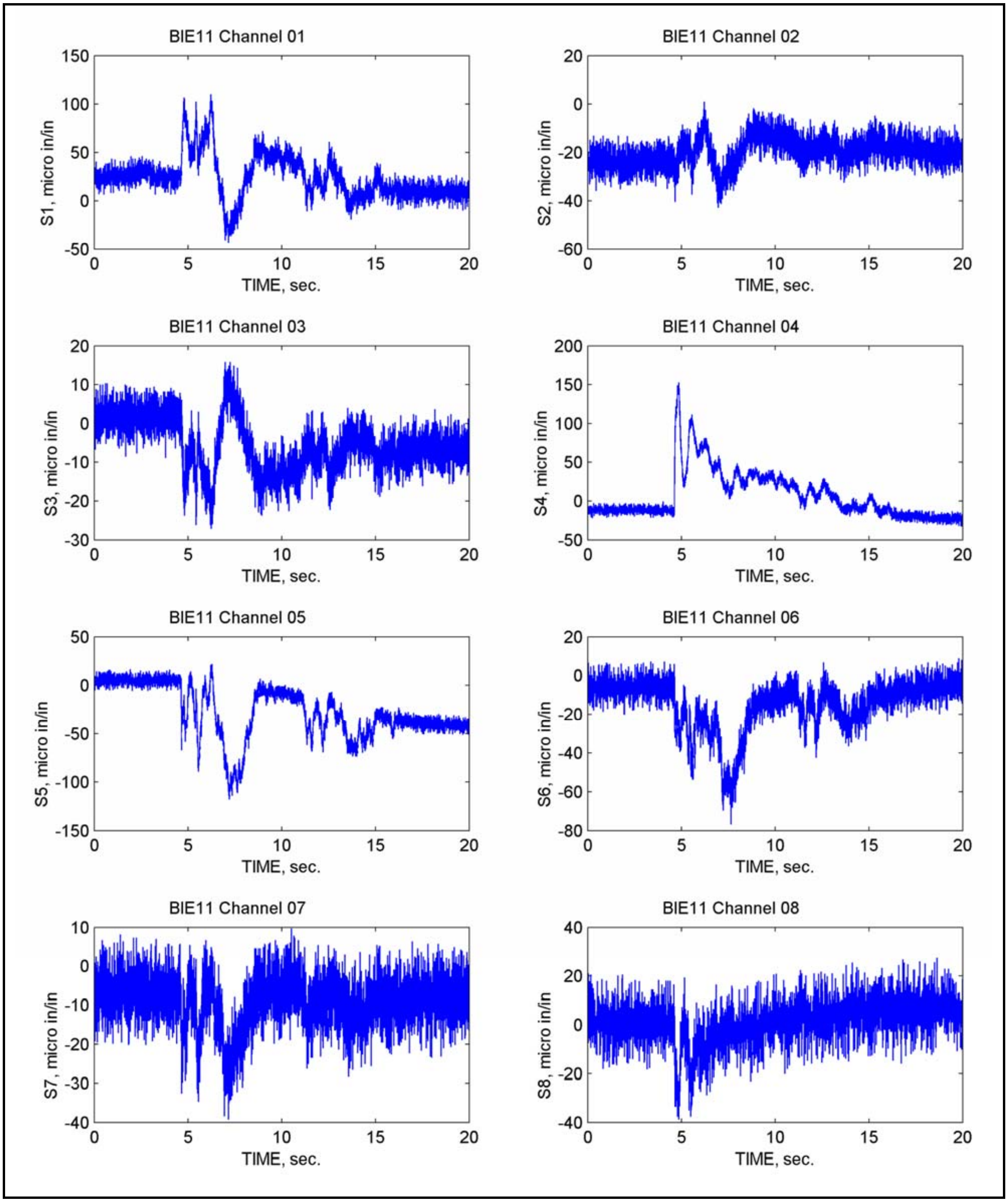
Patev, R. C., Barker, B. C, and Koestler, Leo V., III. (2003). "Prototype Barge Impact Experiments, Allegheny Lock and Dam 2, Pittsburgh, PA," Technical Report ERDC/ITL TR-03-2, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Appendix A
Raw Experiment Data Plots—Barge Instrumentation

Representative plots of the raw data from the barge instrumentation are presented here to show the general trends recorded with the data that were collected.

The experiments from which the data plots were derived are indicated. The reference for each instrument (e.g., S1) in each plot can be determined from Tables 5.1-5.4.

Caveat to the reader: These plots are purely raw data on scaled plots. Interpretation and any further use of these data are subject to possible misinterpretation by those unfamiliar with how the data were recorded and the type of instrumentation used to collect the data.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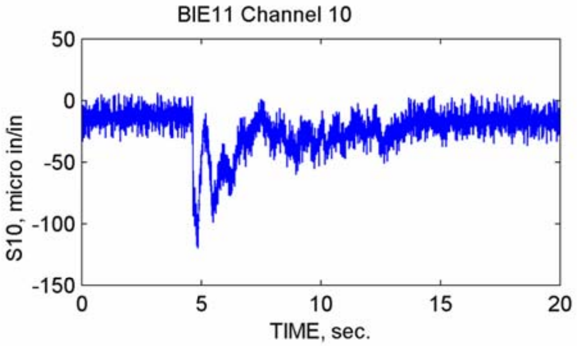
TIME, sec.
BIE11 Channel 02
S2, micro in/in
TIME, sec.
BIE11 Channel 03
S3, micro in/in
TIME, sec.
BIE11 Channel 04
S4, micro in/in
TIME, sec.
BIE11 Channel 05
S5, micro in/in
TIME, sec.
BIE11 Channel 06
S6, micro in/in
TIME, sec.
BIE11 Channel 07
S7, micro in/in
TIME, sec.
BIE11 Channel 08
S8, micro in/in
TIME, sec.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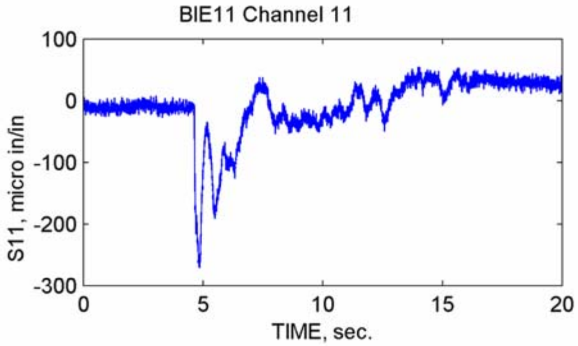
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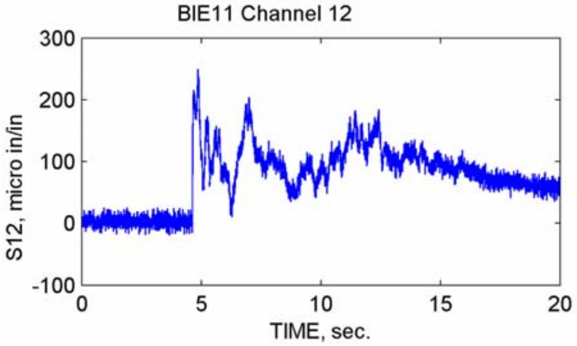
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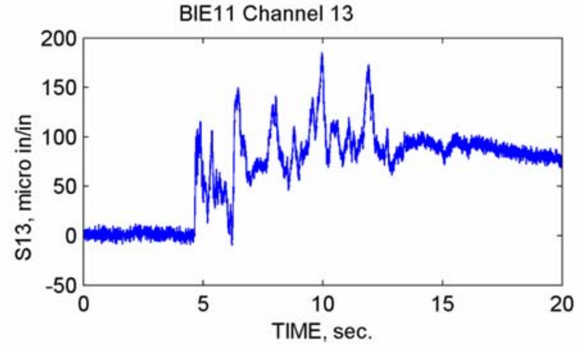
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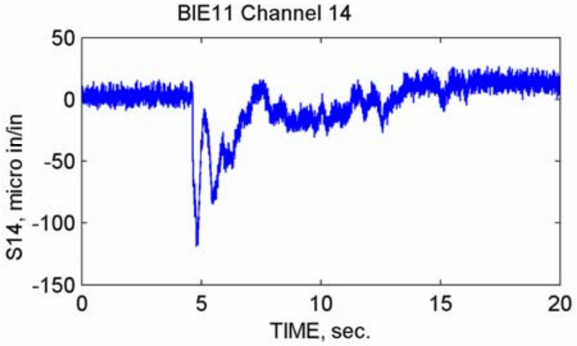
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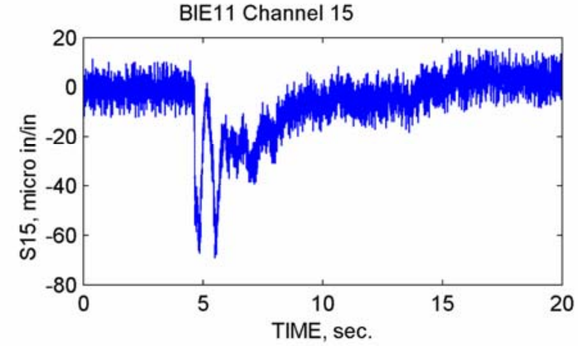
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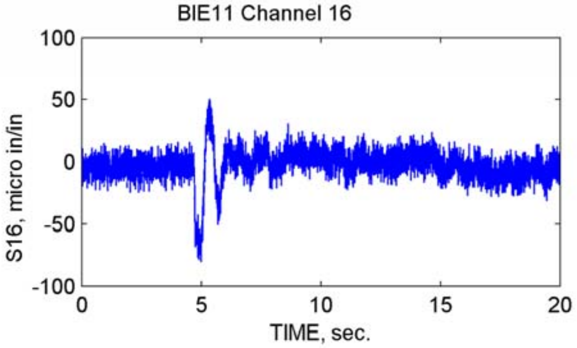
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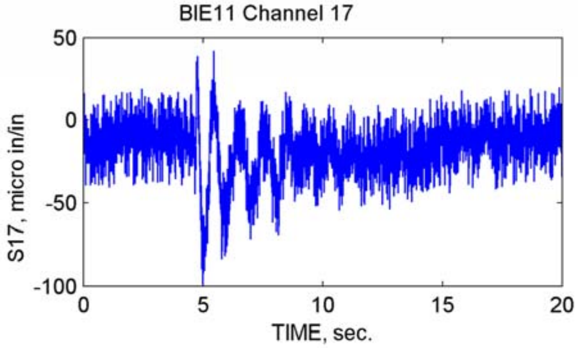
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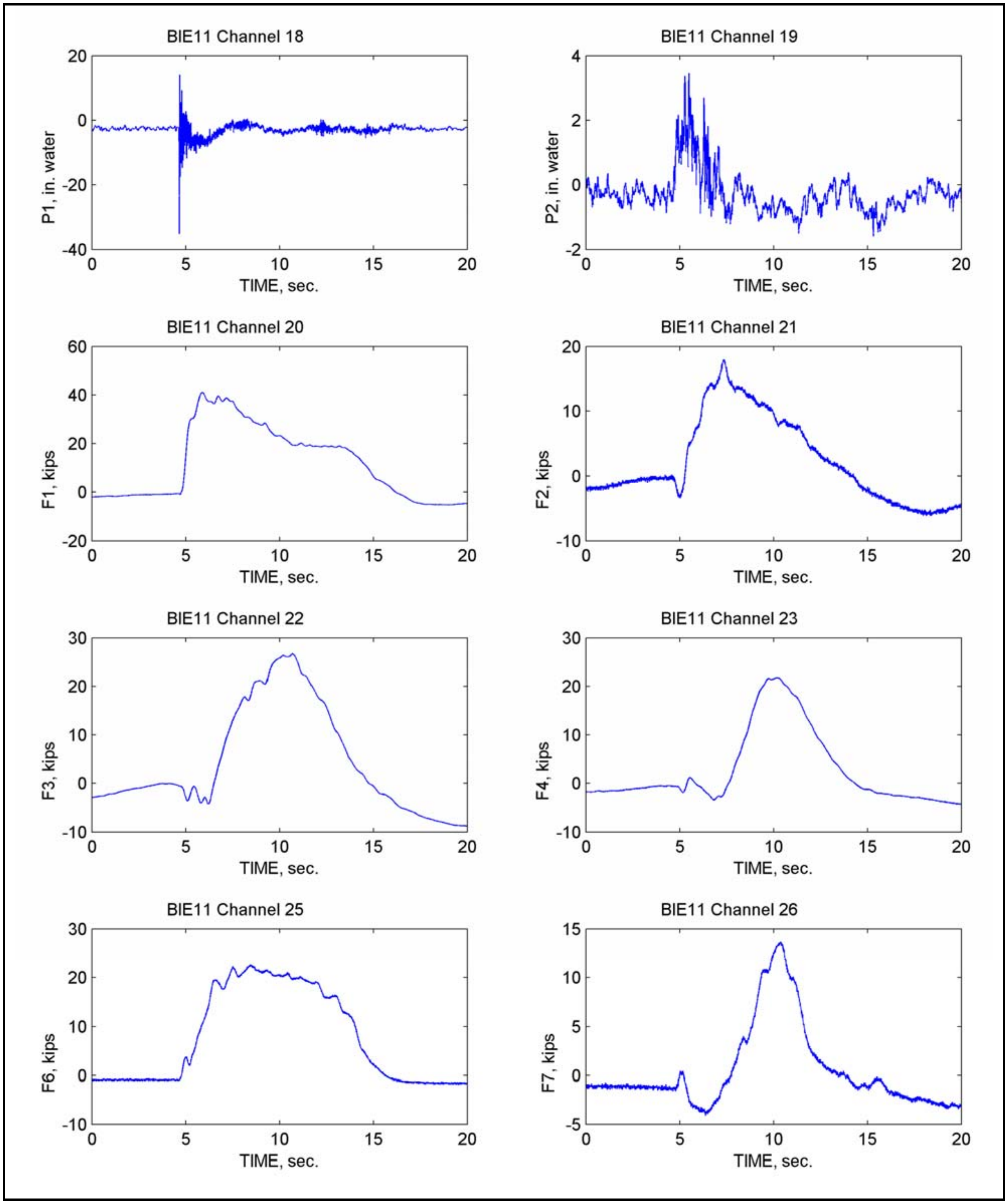
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0
5
10
15
20
BIE11 Channel 19
P2, in. water
4
2
0
-2
TIME, sec.
BIE11 Channel 20
F1, kips
60
40
20
0
-20
TIME, sec.
BIE11 Channel 21
F2, kips
20
10
0
-10
TIME, sec.
BIE11 Channel 22
F3, kips
30
20
10
0
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TIME, sec.
BIE11 Channel 23
F4, kips
30
20
10
0
-10
TIME, sec.
BIE11 Channel 25
F6, kips
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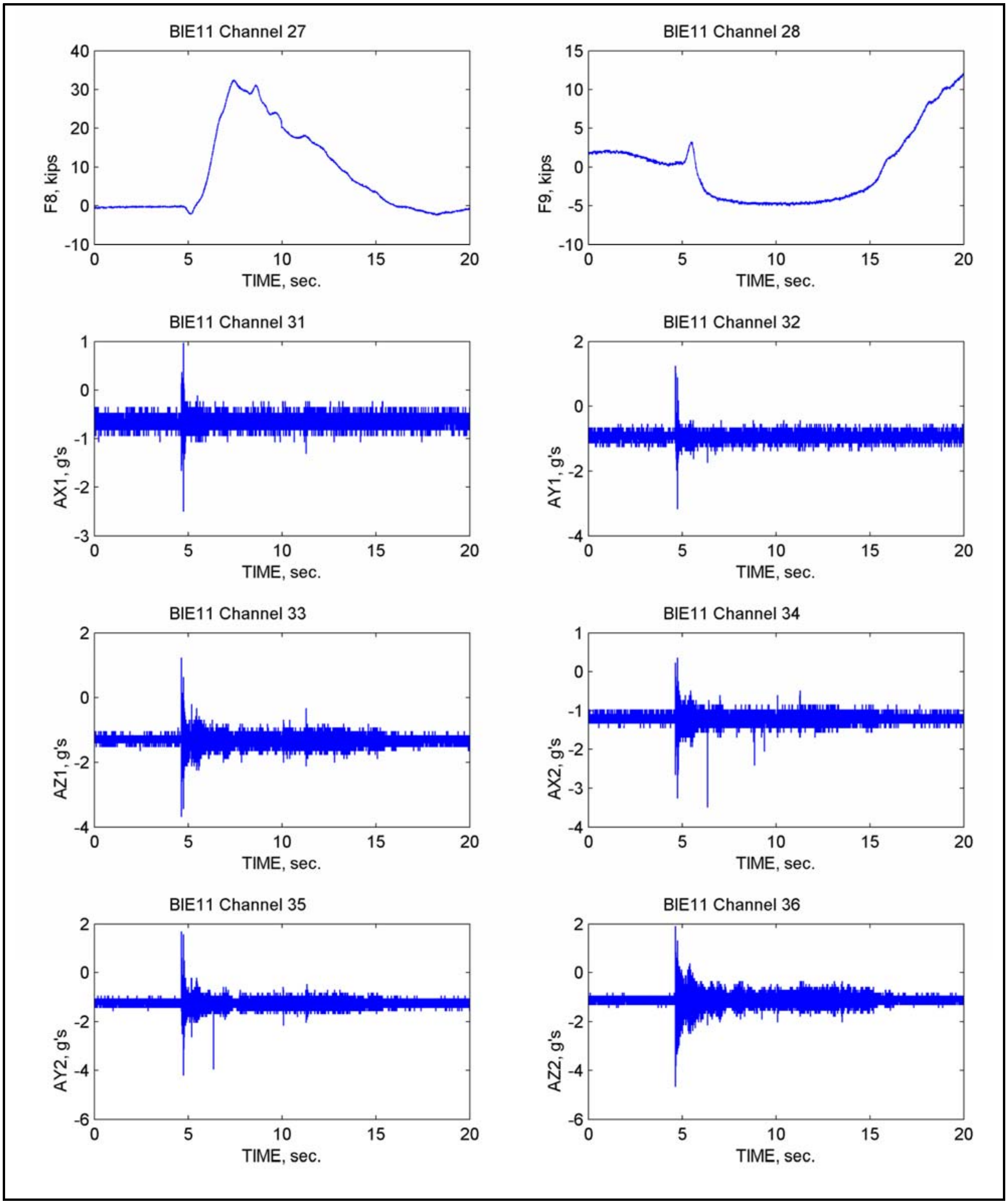
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F9, kips
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10
5
0
-5
-10
TIME, sec.
0
5
10
15
20
BIE11 Channel 31
AX1, g's
1
0
-1
-2
-3
TIME, sec.
0
5
10
15
20
BIE11 Channel 32
AY1, g's
2
0
-2
-4
TIME, sec.
0
5
10
15
20
BIE11 Channel 33
AZ1, g's
2
0
-2
-4
TIME, sec.
0
5
10
15
20
BIE11 Channel 34
AX2, g's
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-2
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AY2, g's
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15
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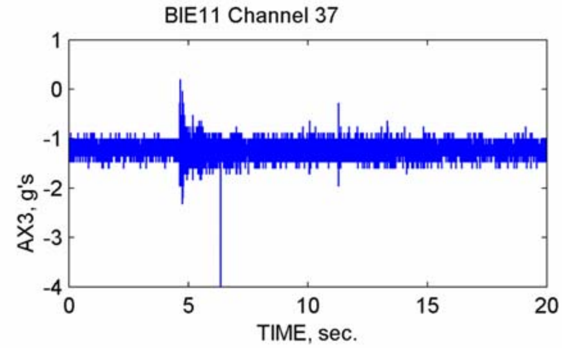
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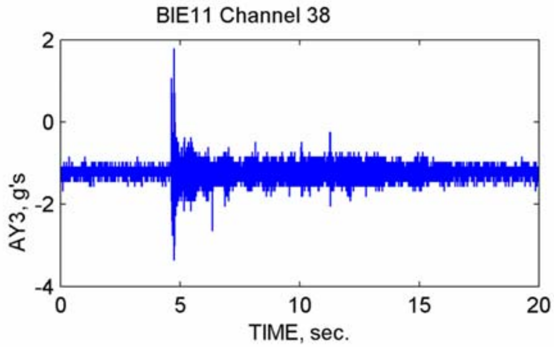
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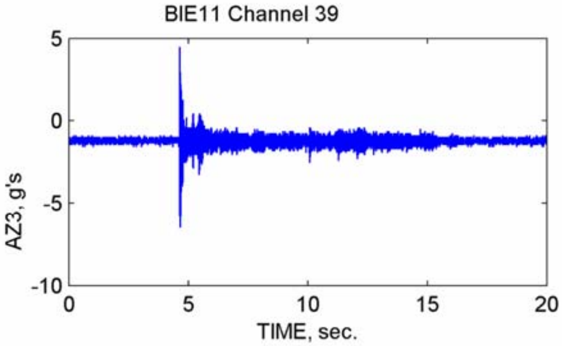
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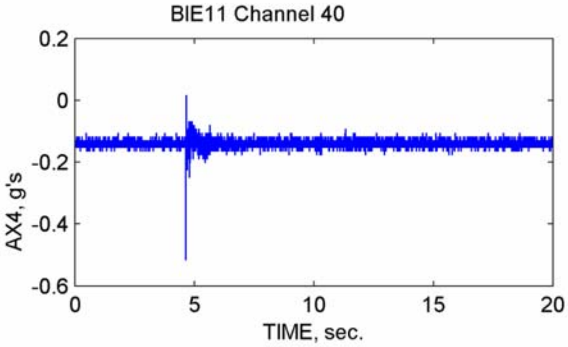
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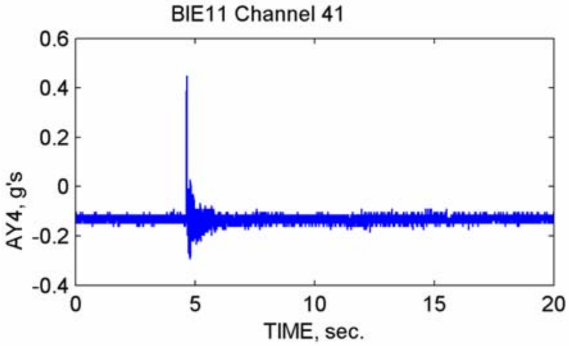
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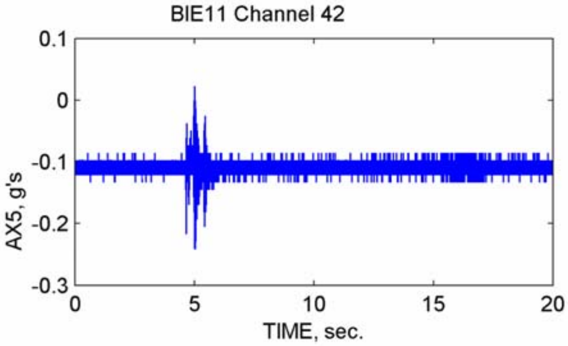
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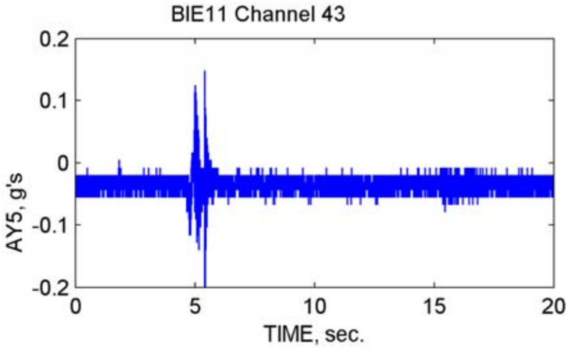
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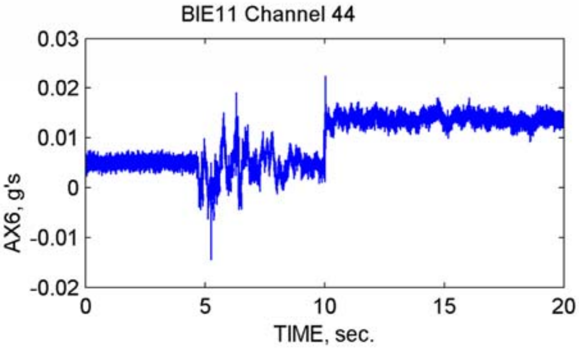
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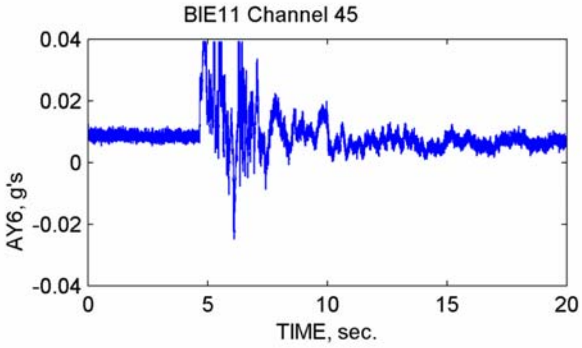
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15
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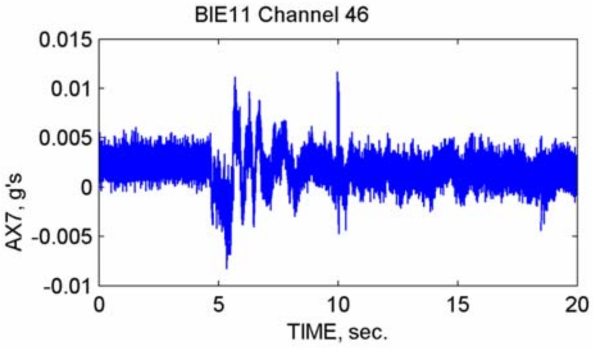
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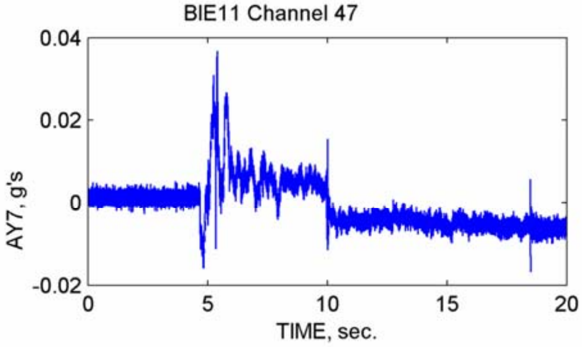
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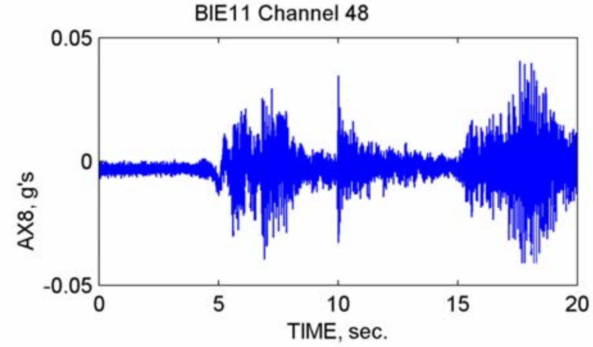
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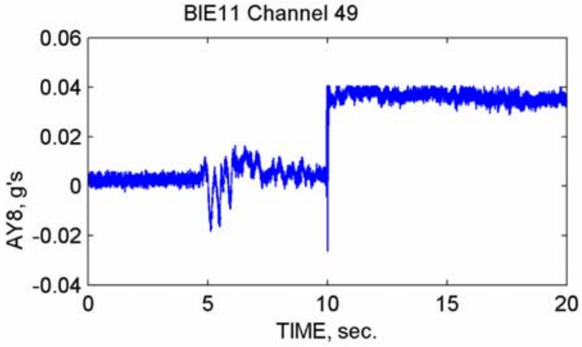
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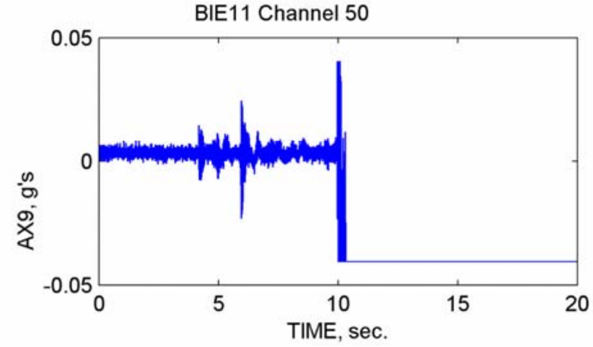
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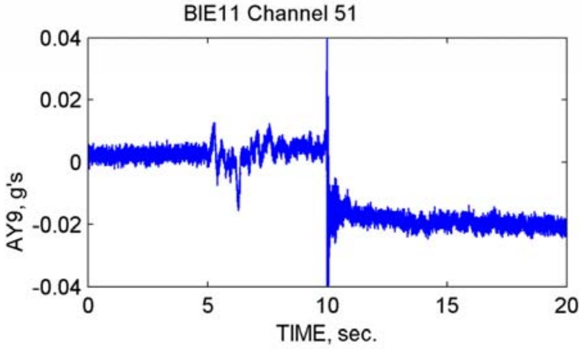
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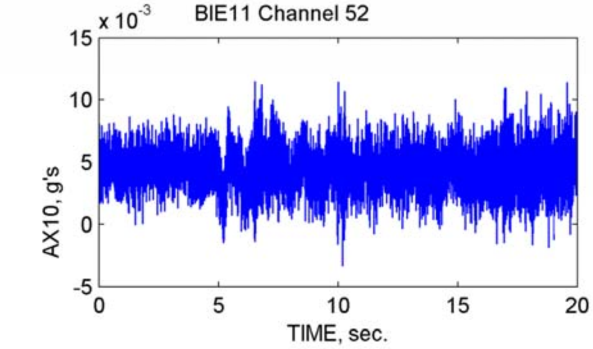
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AX10, g's
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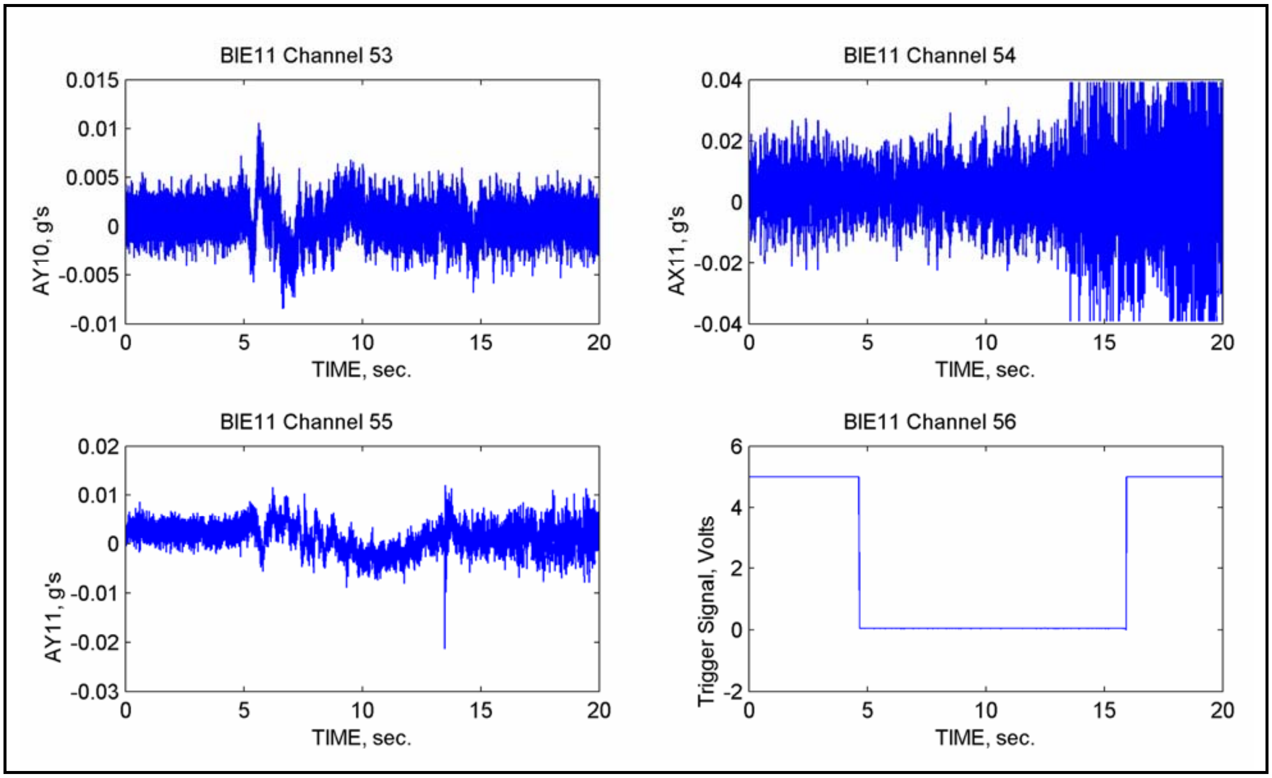
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TIME, sec.
BIE11 Channel 54
AX11, g's
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20
TIME, sec.
BIE11 Channel 55
AY11, g's
0.02
0.01
0
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0
5
10
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Trigger Signal, Volts
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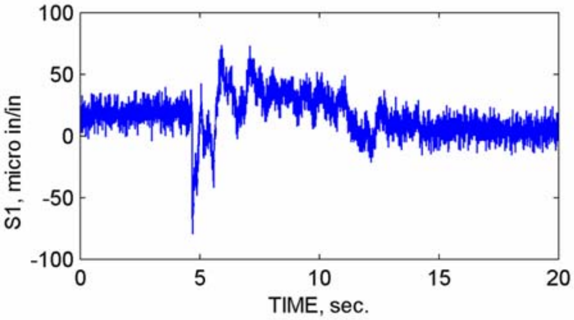
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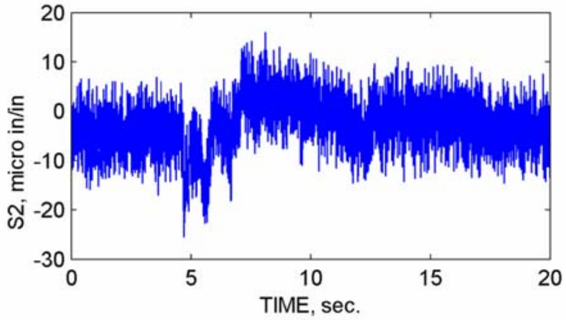
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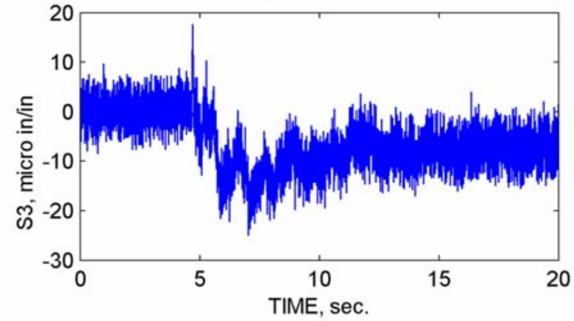
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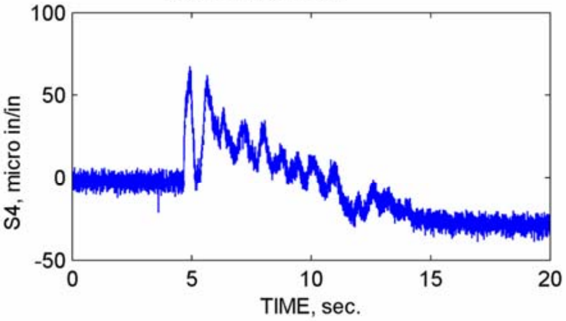
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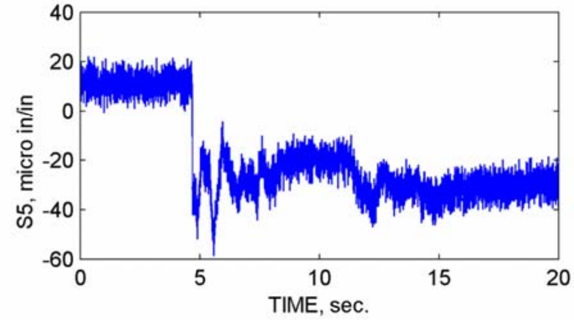
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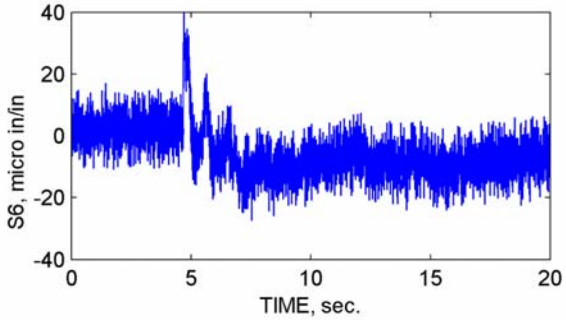
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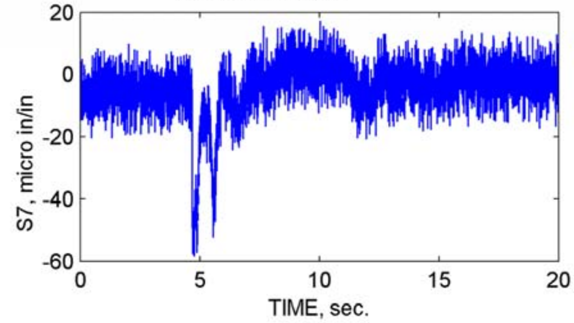
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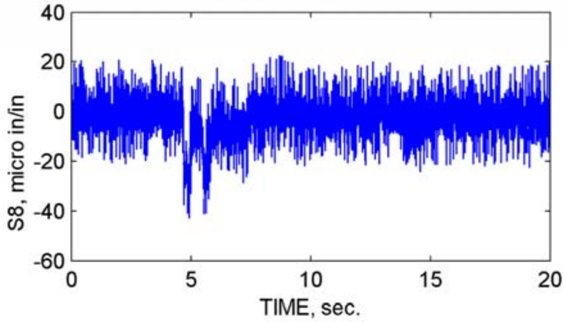
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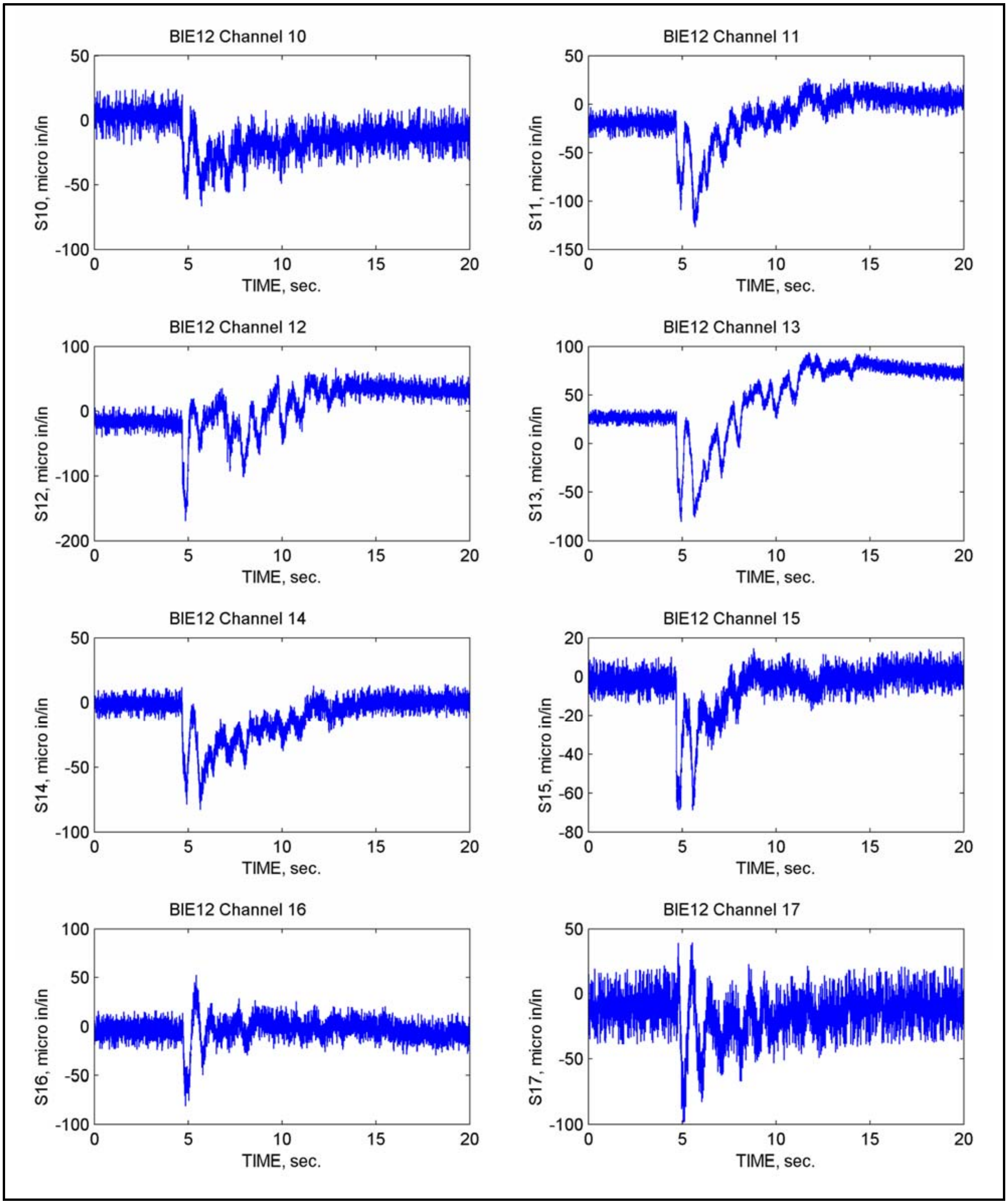

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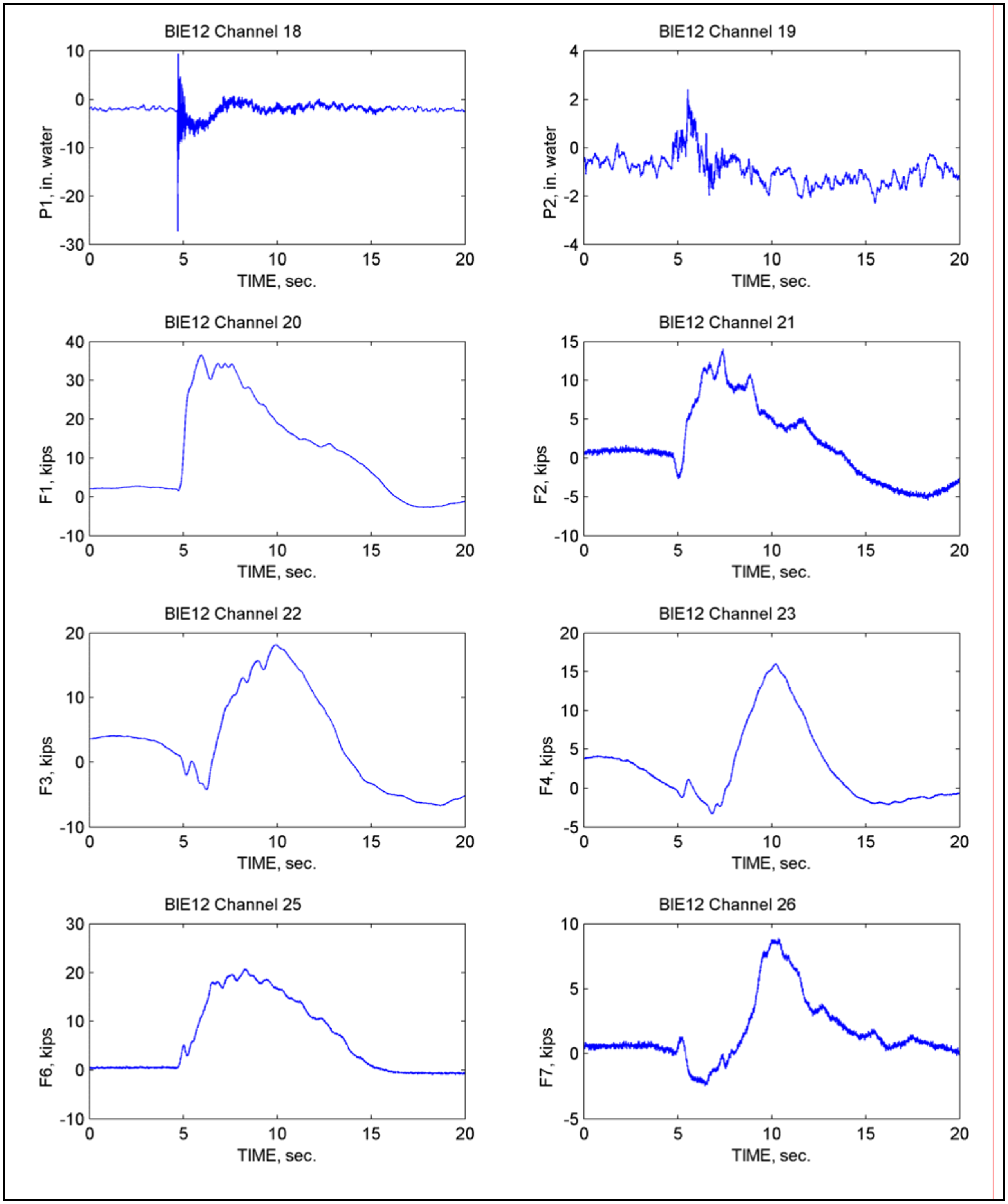
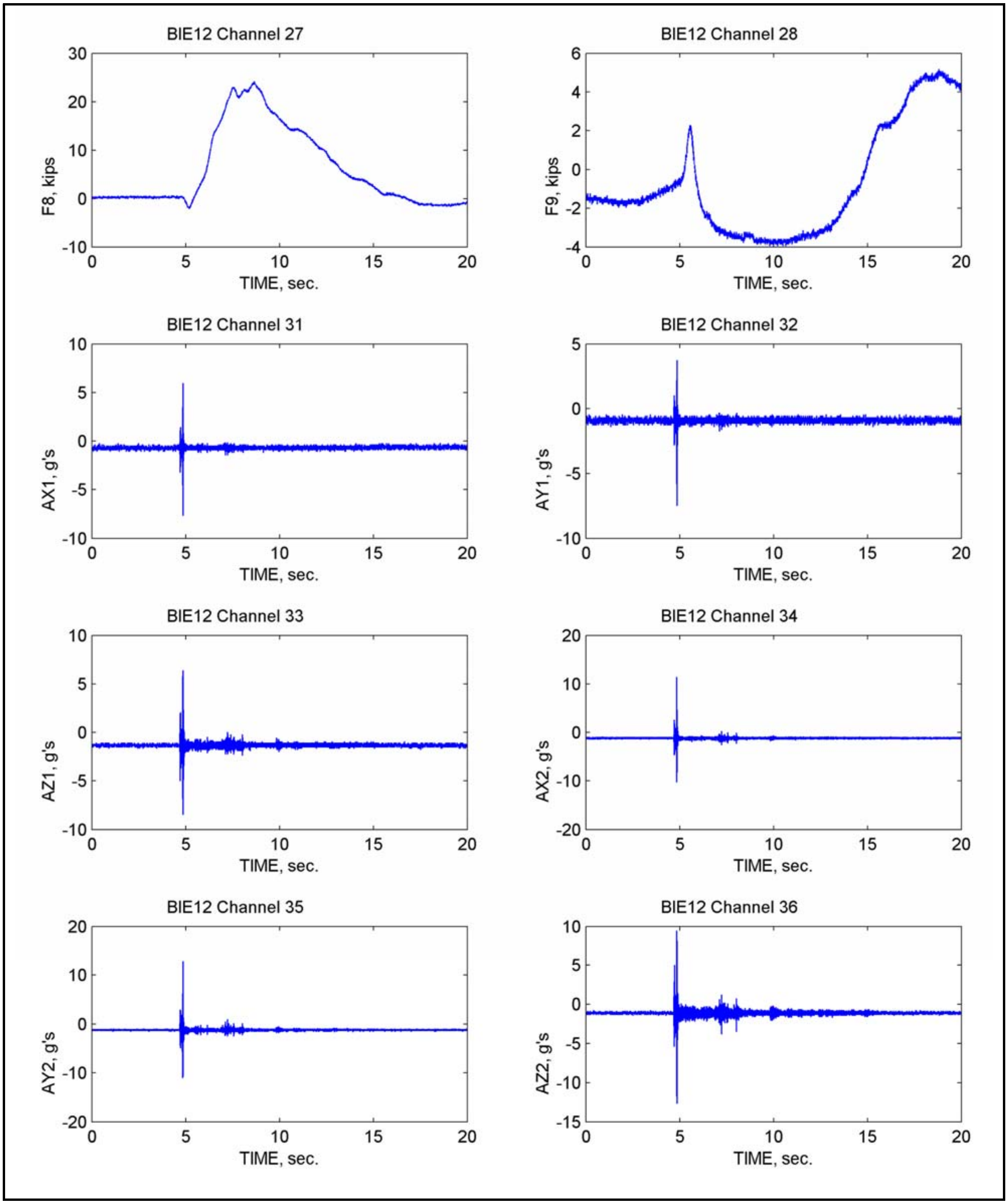
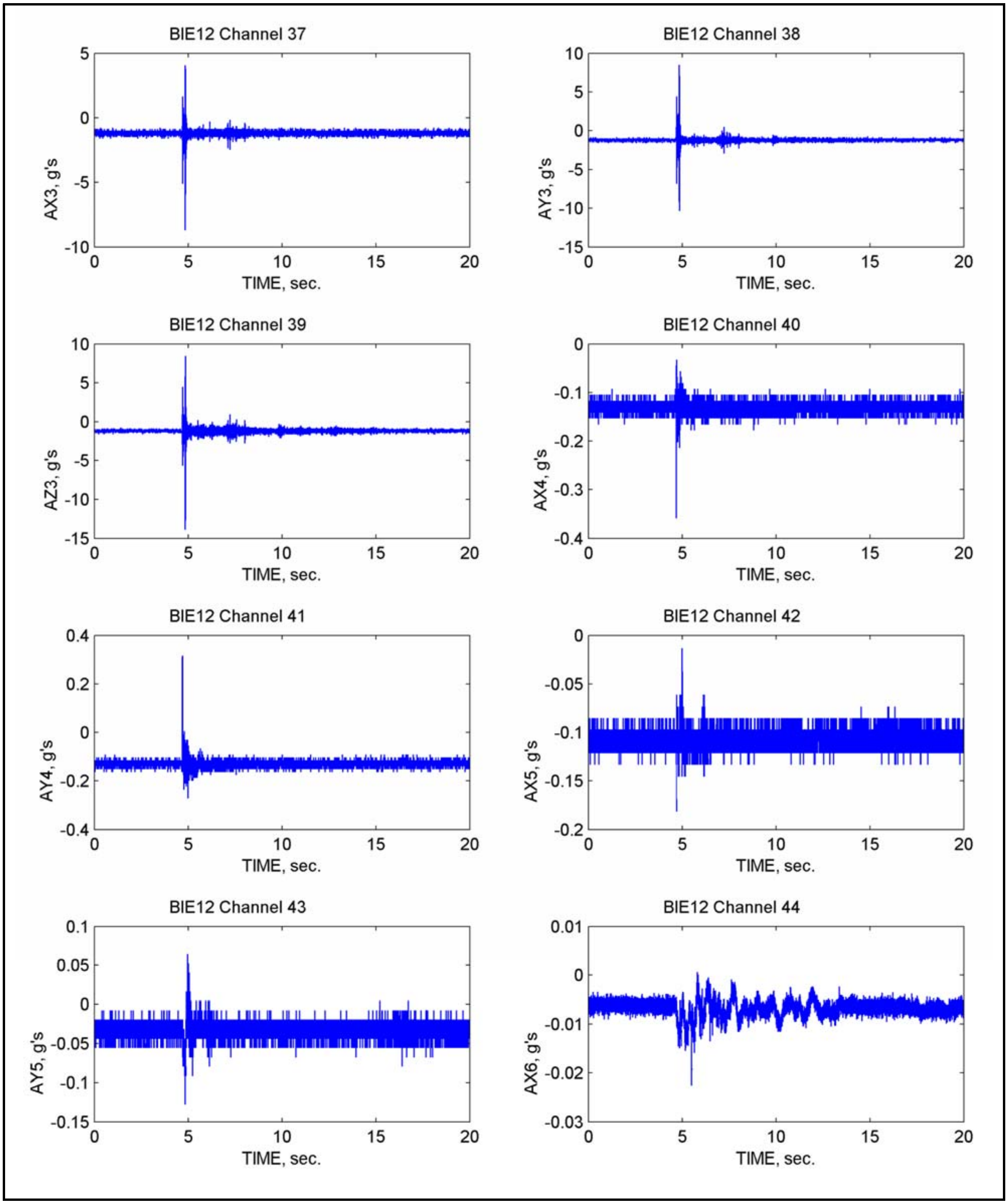
BIE12 Channel 16

BIE12 Channel 17


BIE12 Channel 18
P1, in. water
10
0
-10
-20
-30
0
5
10
15
20
TIME, sec.
BIE12 Channel 19
P2, in. water
4
2
0
-2
-4
0
5
10
15
20
TIME, sec.
BIE12 Channel 20
F1, kips
40
30
20
10
0
-10
0
5
10
15
20
TIME, sec.
BIE12 Channel 21
F2, kips
15
10
5
0
-5
-10
0
5
10
15
20
TIME, sec.
BIE12 Channel 22
F3, kips
20
10
0
-10
0
5
10
15
20
TIME, sec.
BIE12 Channel 23
F4, kips
20
15
10
5
0
-5
0
5
10
15
20
TIME, sec.
BIE12 Channel 25
F6, kips
30
20
10
0
-10
0
5
10
15
20
TIME, sec.
BIE12 Channel 26
F7, kips
10
5
0
-5
0
5
10
15
20
TIME, sec.


BIE12 Channel 27
F8, kips
30
20
10
0
-10
0
5
10
15
20
TIME, sec.
BIE12 Channel 28
F9, kips
6
4
2
0
-2
-4
0
5
10
15
20
TIME, sec.
BIE12 Channel 31
AX1, g's
10
5
0
-5
-10
0
5
10
15
20
TIME, sec.
BIE12 Channel 32
AY1, g's
5
0
-5
-10
0
5
10
15
20
TIME, sec.
BIE12 Channel 33
AZ1, g's
10
5
0
-5
-10
0
5
10
15
20
TIME, sec.
BIE12 Channel 34
AX2, g's
20
10
0
-10
-20
0
5
10
15
20
TIME, sec.
BIE12 Channel 35
AY2, g's
20
10
0
-10
-20
0
5
10
15
20
TIME, sec.
BIE12 Channel 36
AZ2, g's
10
5
0
-5
-10
-15
0
5
10
15
20
TIME, sec.


BIE12 Channel 37

BIE12 Channel 38

BIE12 Channel 39

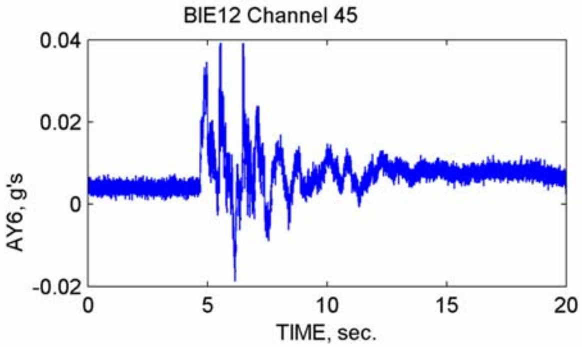
BIE12 Channel 40

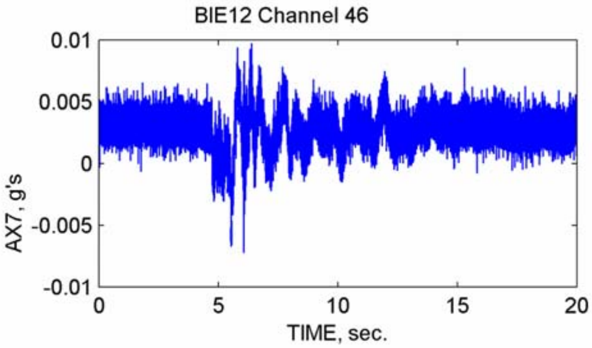
BIE12 Channel 41

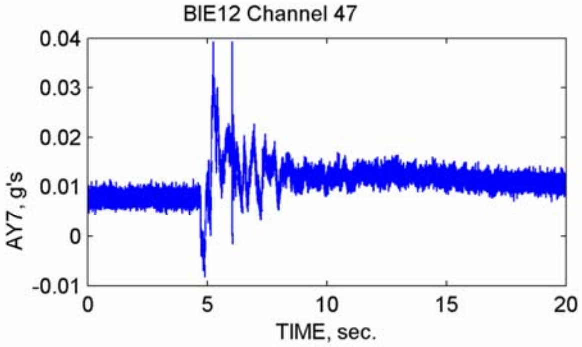
BIE12 Channel 42

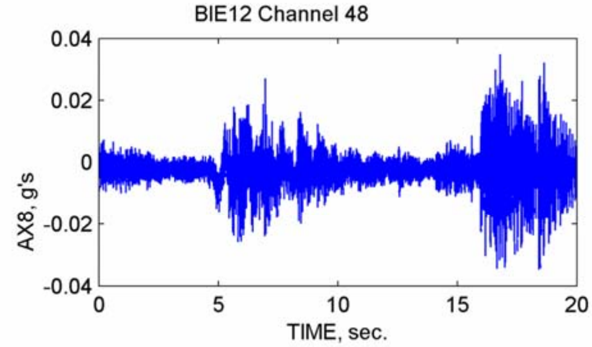
BIE12 Channel 43

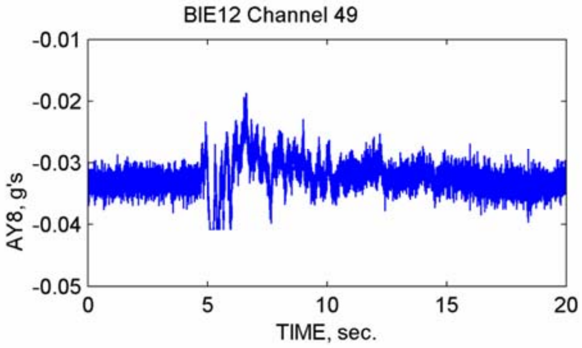
BIE12 Channel 44

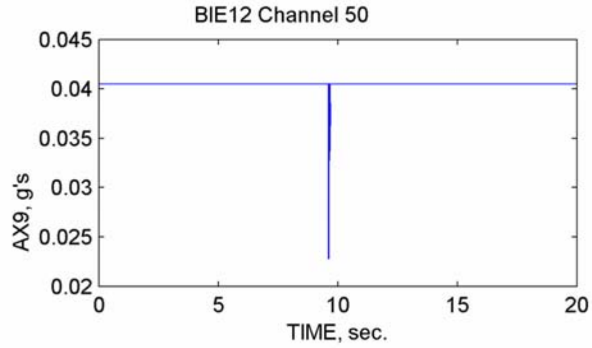

BIE12 Channel 45
AY6, g's
0.04
0.02
0
-0.02
0
5
10
15
20
TIME, sec.

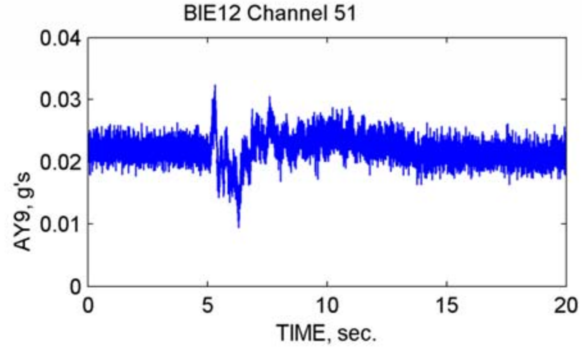

BIE12 Channel 46
AX7, g's
0.01
0.005
0
-0.005
-0.01
0
5
10
15
20
TIME, sec.

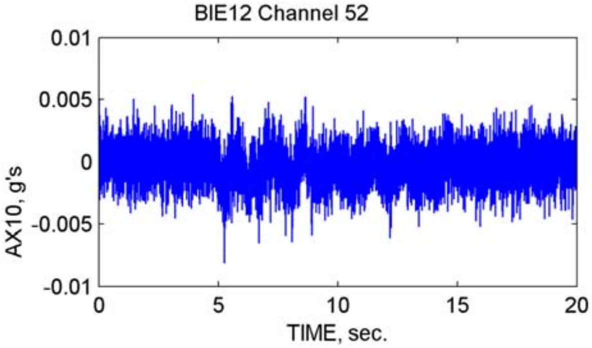

BIE12 Channel 47
AY7, g's
0.04
0.03
0.02
0.01
0
-0.01
0
5
10
15
20
TIME, sec.

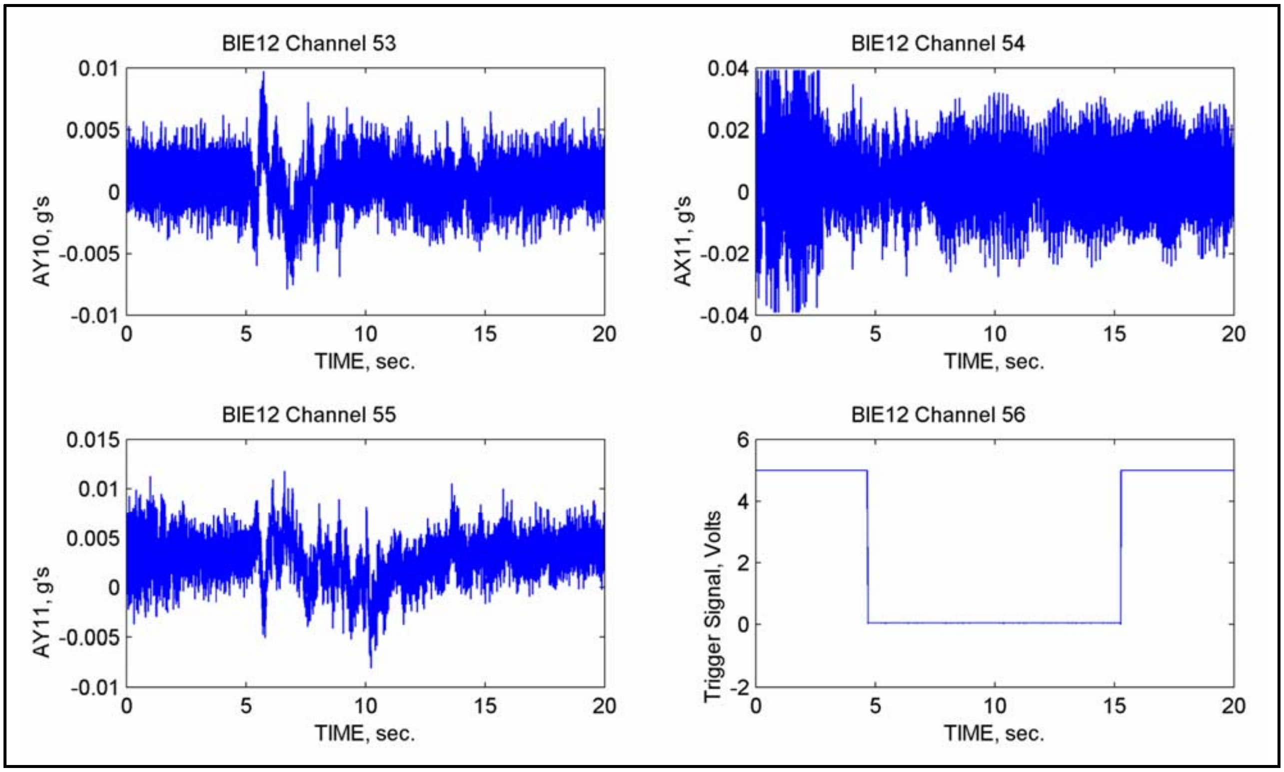

BIE12 Channel 48
AX8, g's
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20
TIME, sec.

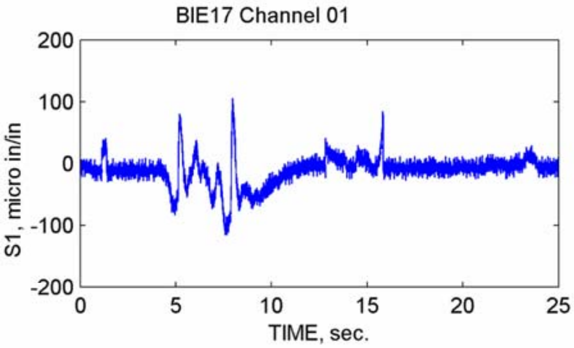

BIE12 Channel 49
AY8, g's
-0.01
-0.02
-0.03
-0.04
-0.05
0
5
10
15
20
TIME, sec.

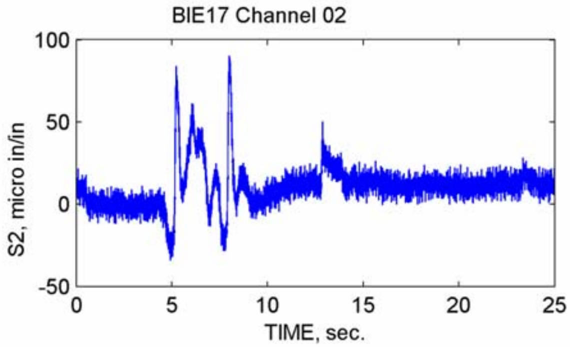

BIE12 Channel 50
AX9, g's
0.045
0.04
0.035
0.03
0.025
0.02
0
5
10
15
20
TIME, sec.

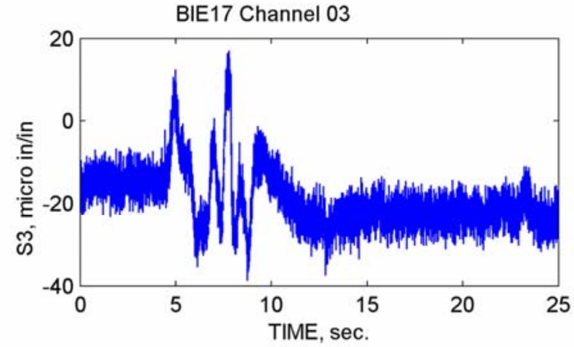

BIE12 Channel 51
AY9, g's
0.04
0.03
0.02
0.01
0
0
5
10
15
20
TIME, sec.

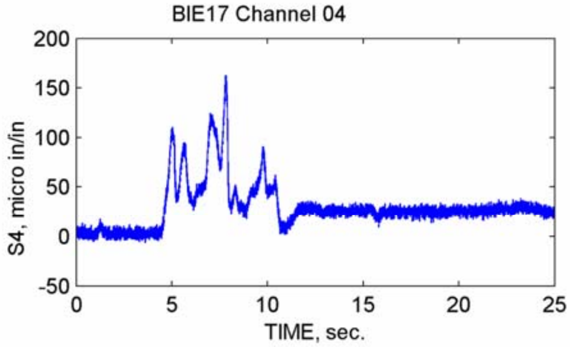

BIE12 Channel 52
AX10, g's
0.01
0.005
0
-0.005
-0.01
0
5
10
15
20
TIME, sec.

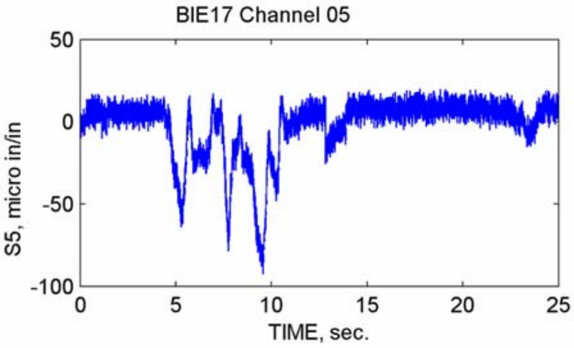

BIE12 Channel 53
AY10, g's
0.01
0.005
0
-0.005
-0.01
TIME, sec.
0
5
10
15
20
BIE12 Channel 54
AX11, g's
0.04
0.02
0
-0.02
-0.04
TIME, sec.
BIE12 Channel 55
AY11, g's
0.015
0.01
0.005
0
-0.005
-0.01
TIME, sec.
BIE12 Channel 56
Trigger Signal, Volts
6
4
2
0
-2
TIME, sec.

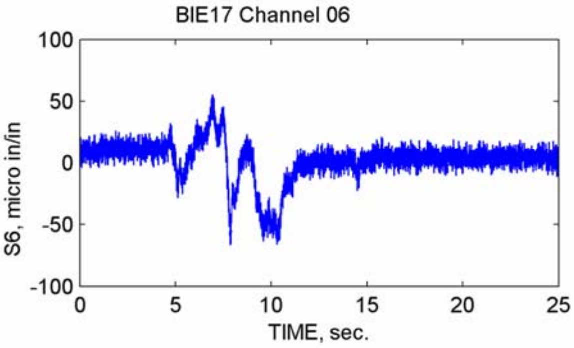

BIE17 Channel 01

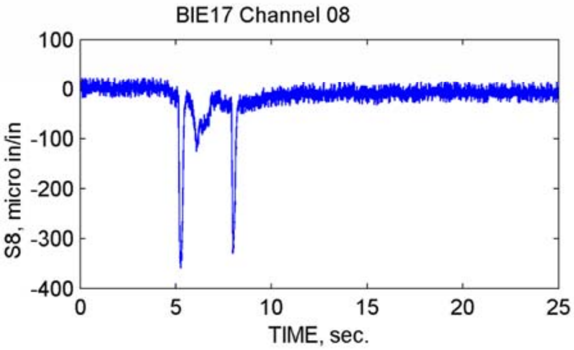

BIE17 Channel 02

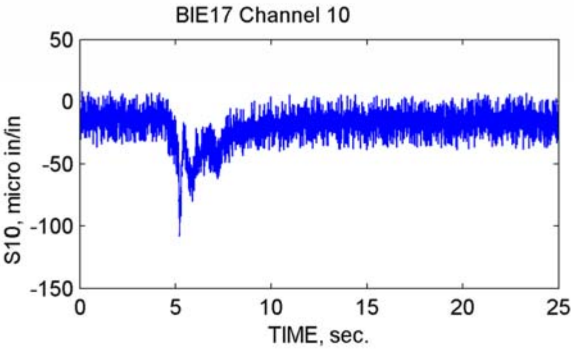

BIE17 Channel 03

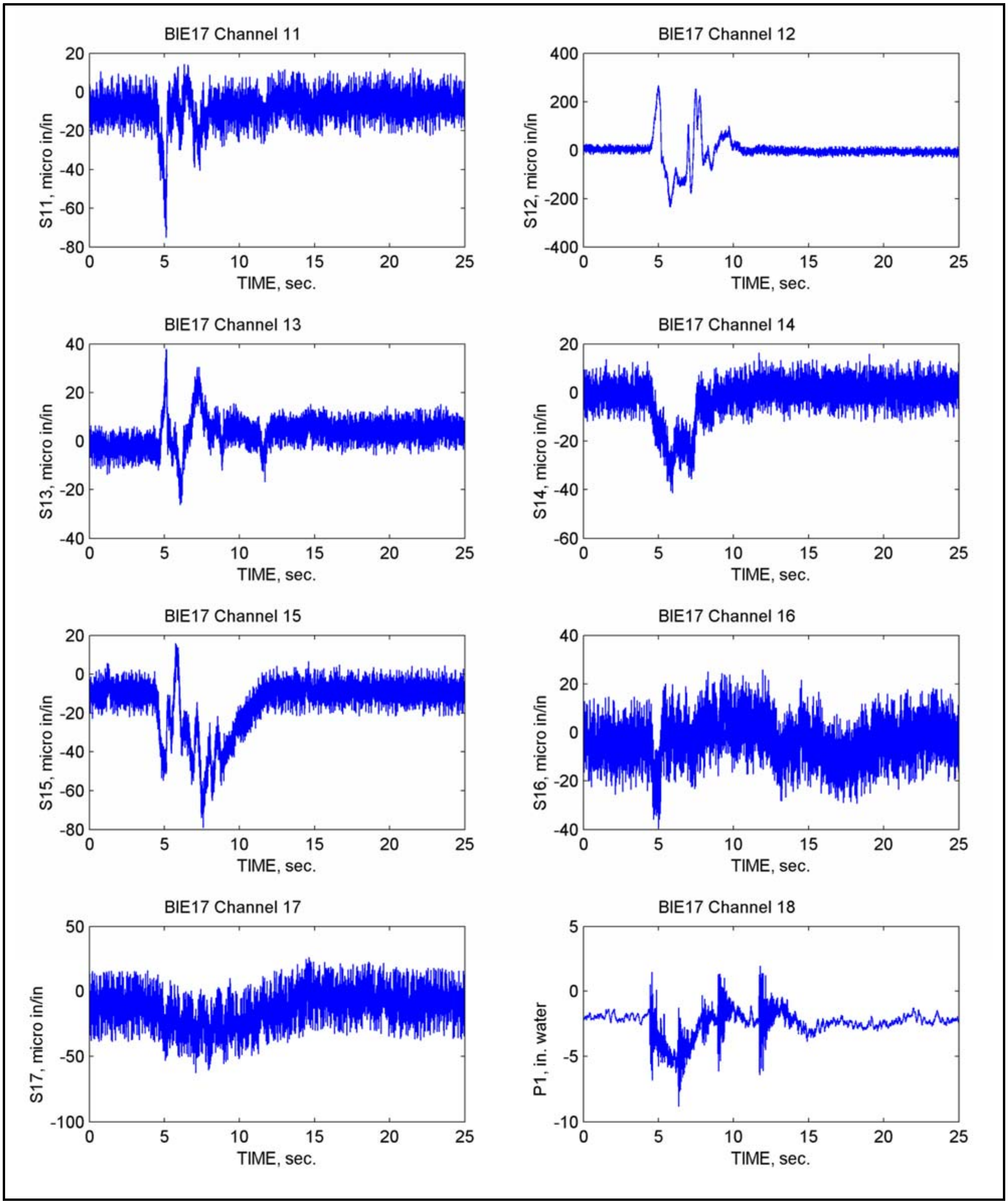

BIE17 Channel 04

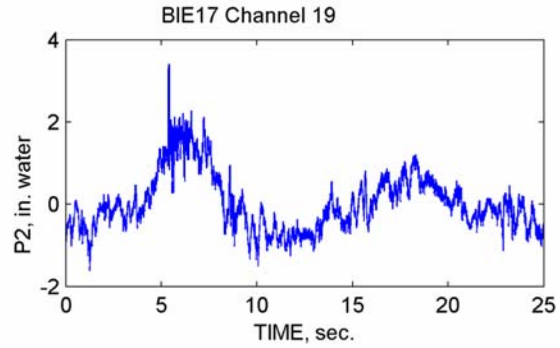

BIE17 Channel 05

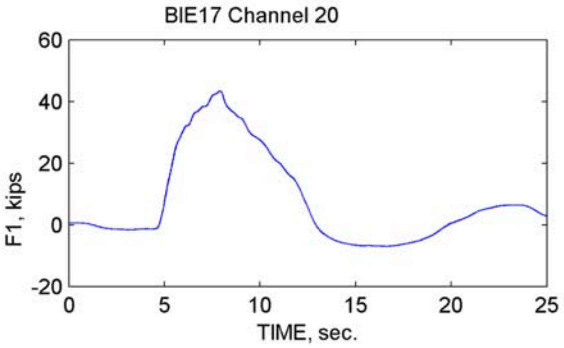

BIE17 Channel 06

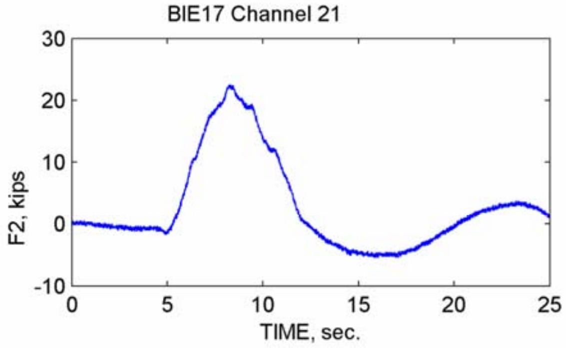

BIE17 Channel 08

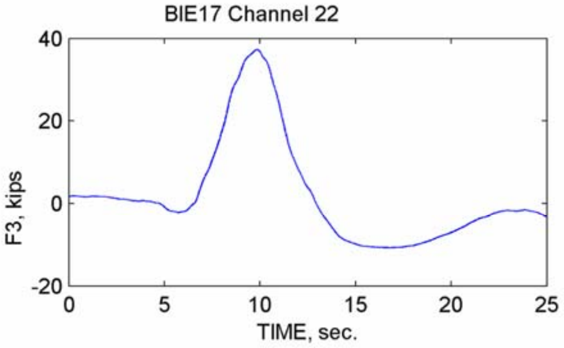

BIE17 Channel 10

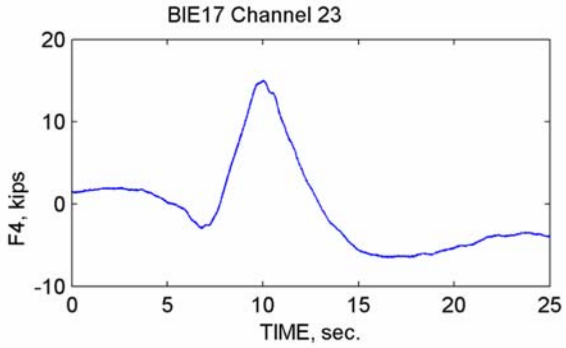

BIE17 Channel 11
S11, micro in/in
20
0
-20
-40
-60
-80
TIME, sec.
0
5
10
15
20
25
BIE17 Channel 12
S12, micro in/in
400
200
0
-200
-400
TIME, sec.
BIE17 Channel 13
S13, micro in/in
40
20
0
-20
-40
TIME, sec.
BIE17 Channel 14
S14, micro in/in
20
0
-20
-40
-60
TIME, sec.
BIE17 Channel 15
S15, micro in/in
20
0
-20
-40
-60
-80
TIME, sec.
BIE17 Channel 16
S16, micro in/in
40
20
0
-20
-40
TIME, sec.
BIE17 Channel 17
S17, micro in/in
50
0
-50
-100
TIME, sec.
BIE17 Channel 18
P1, in. water
5
0
-5
-10
TIME, sec.

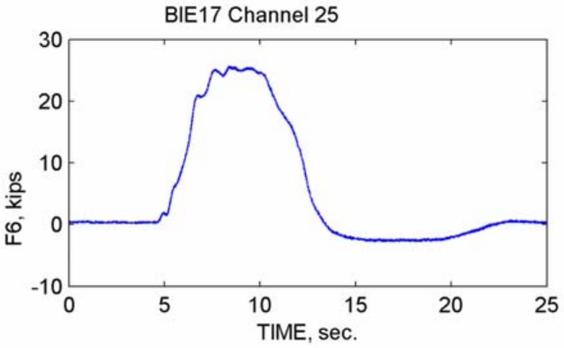

BIE17 Channel 19

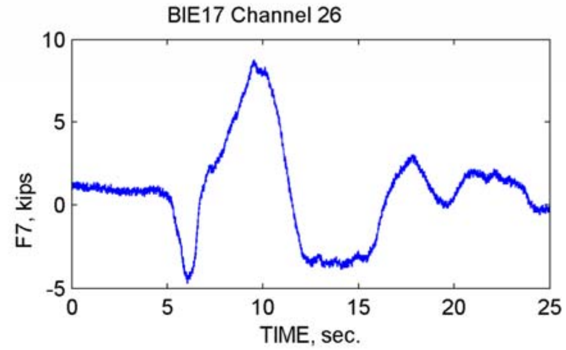

BIE17 Channel 20

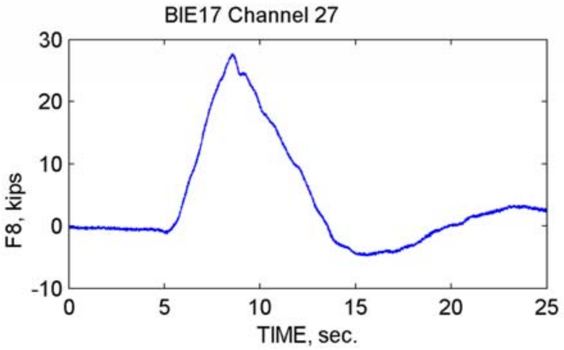

BIE17 Channel 21

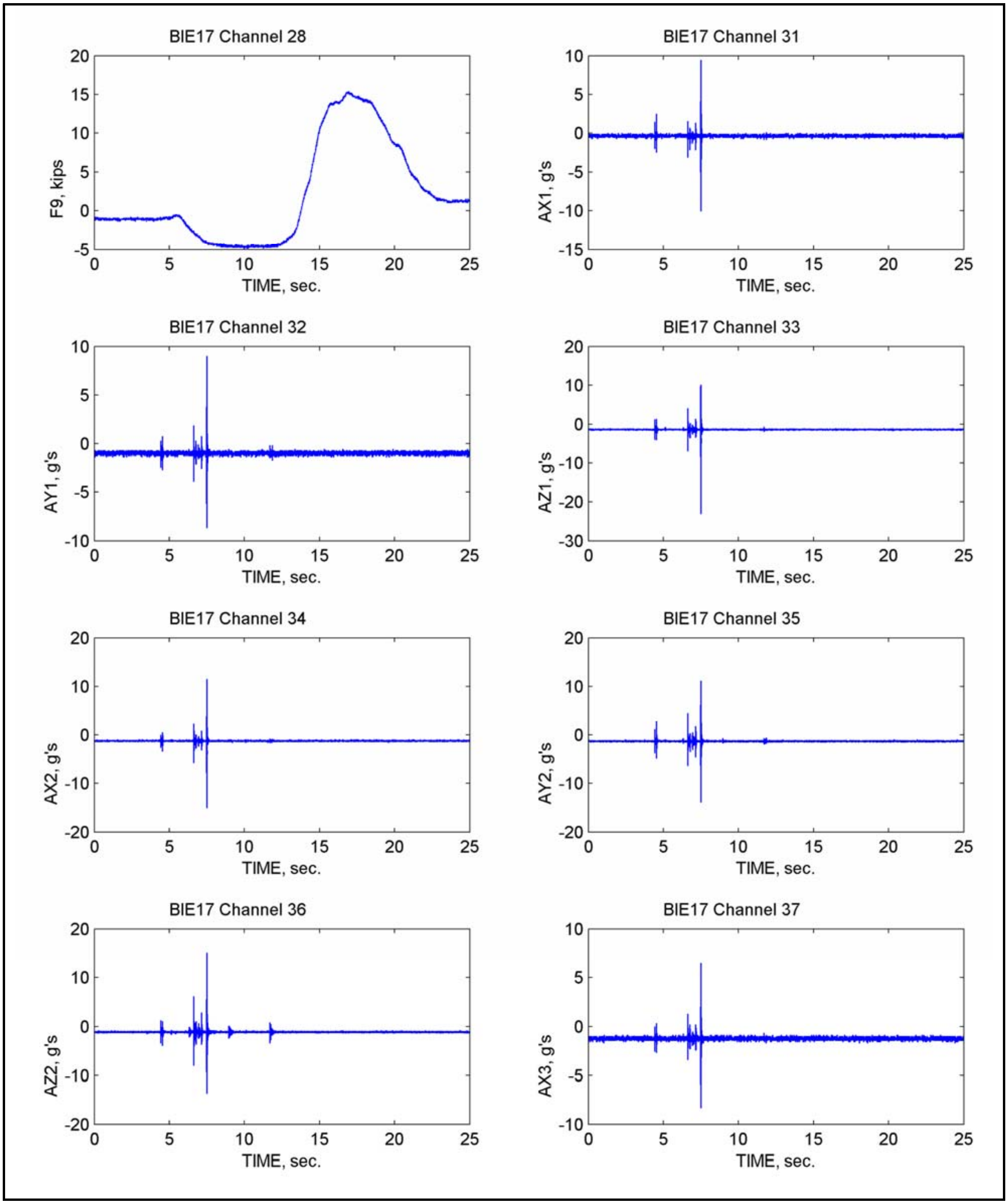

BIE17 Channel 22

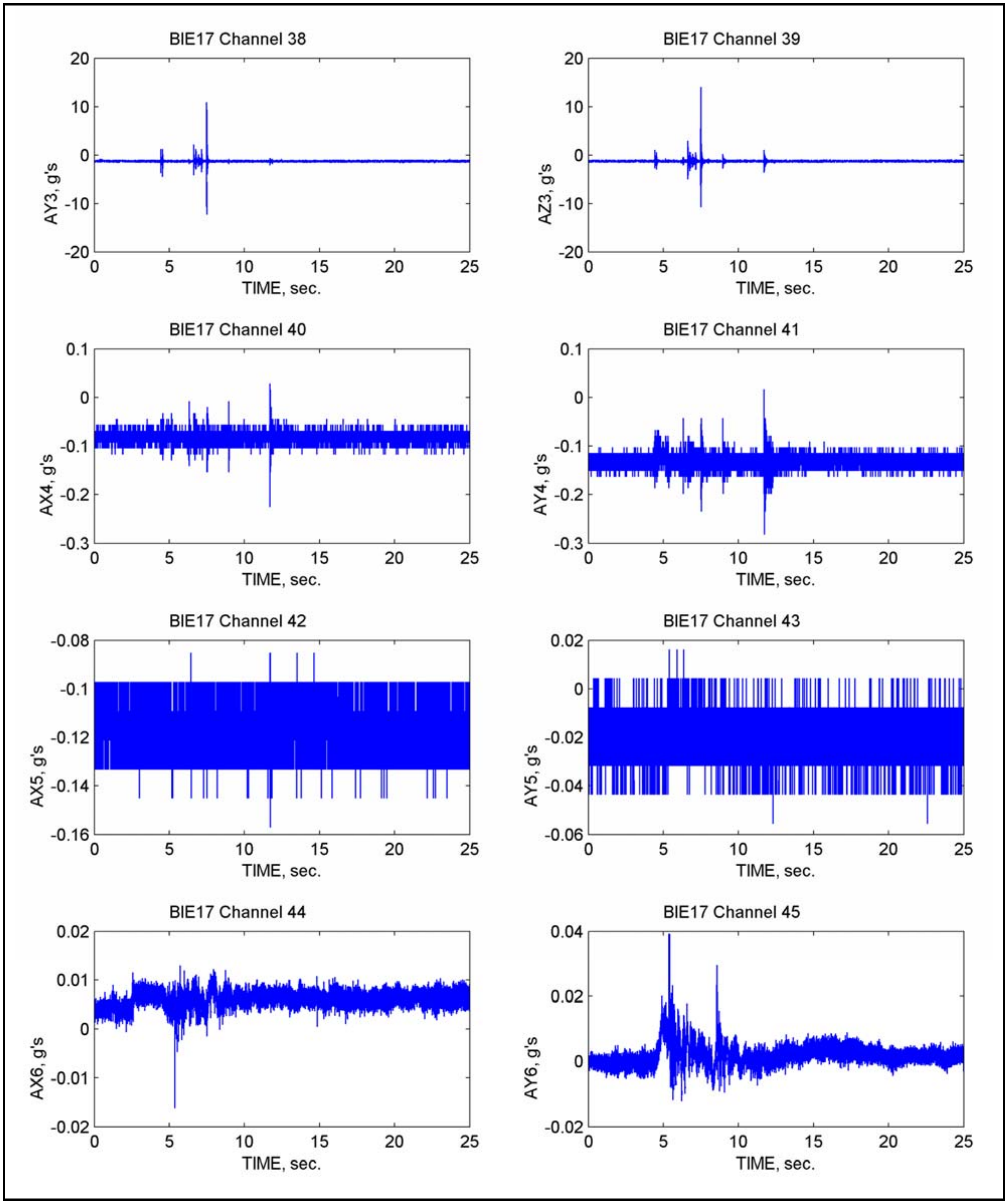

BIE17 Channel 23

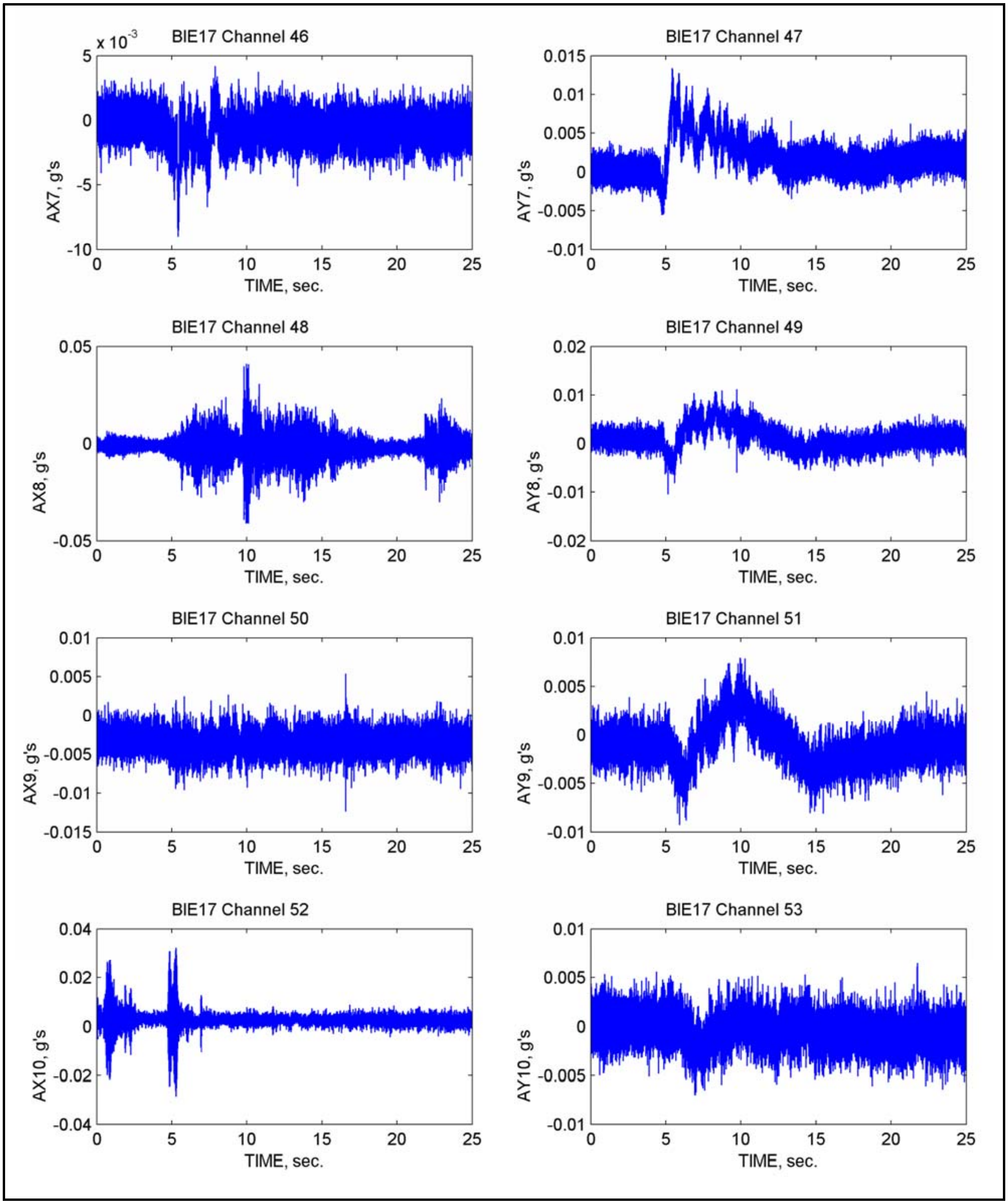

BIE17 Channel 25

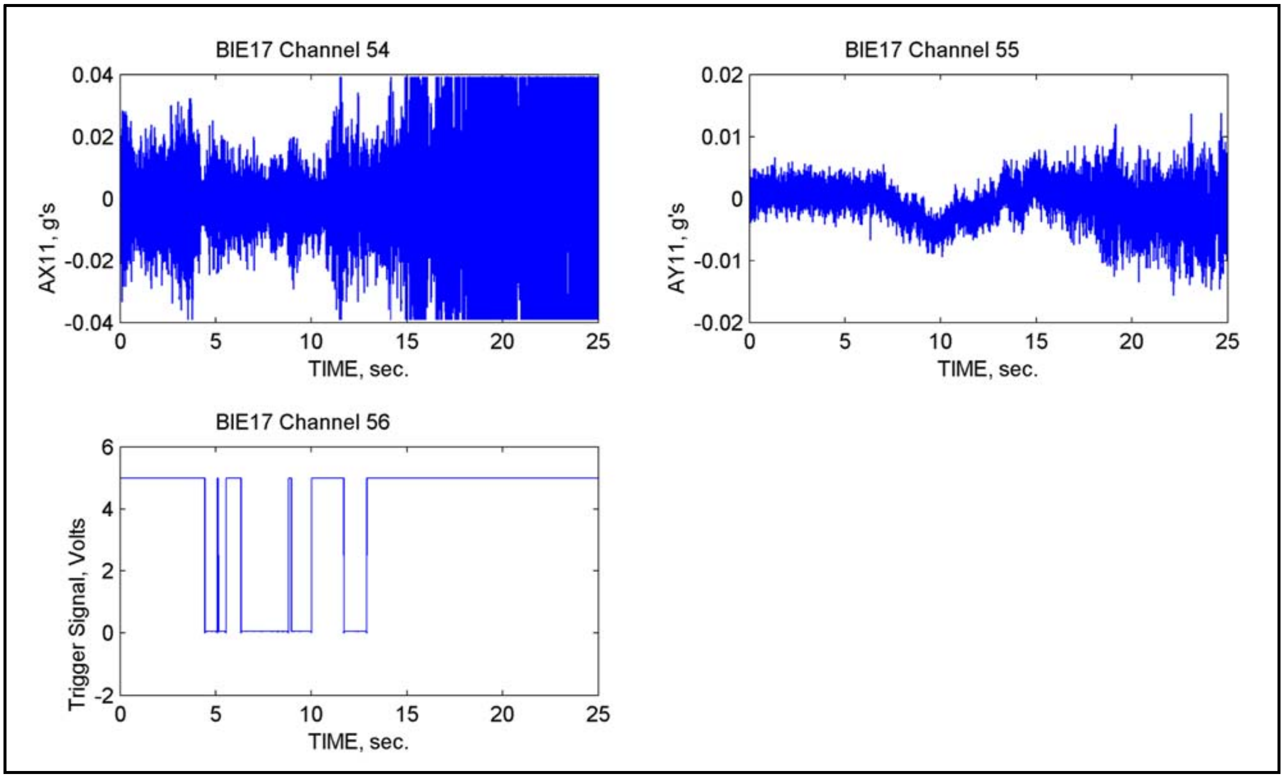

BIE17 Channel 26

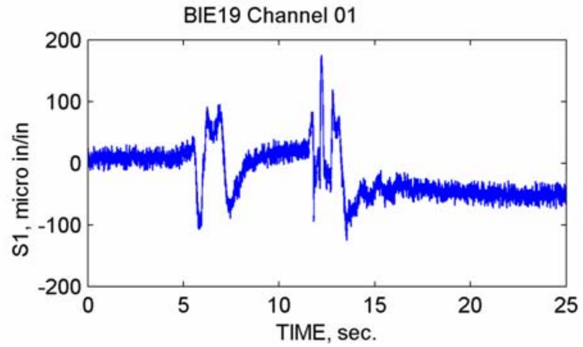

BIE17 Channel 27

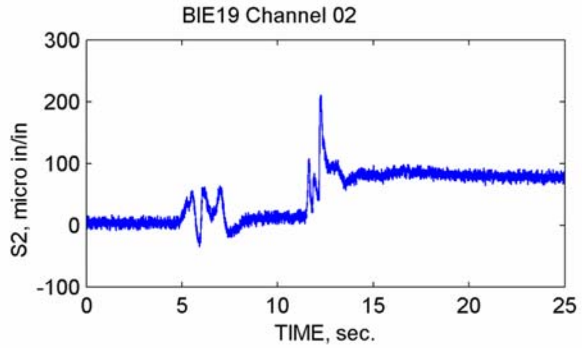

BIE17 Channel 28
F9, kips
20
15
10
5
0
-5
0
5
10
15
20
25
TIME, sec.
BIE17 Channel 31
AX1, g's
10
5
0
-5
-10
-15
0
5
10
15
20
25
TIME, sec.
BIE17 Channel 32
AY1, g's
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.
BIE17 Channel 33
AZ1, g's
20
10
0
-10
-20
-30
0
5
10
15
20
25
TIME, sec.
BIE17 Channel 34
AX2, g's
20
10
0
-10
-20
0
5
10
15
20
25
TIME, sec.
BIE17 Channel 35
AY2, g's
20
10
0
-10
-20
0
5
10
15
20
25
TIME, sec.
BIE17 Channel 36
AZ2, g's
20
10
0
-10
-20
0
5
10
15
20
25
TIME, sec.
BIE17 Channel 37
AX3, g's
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.

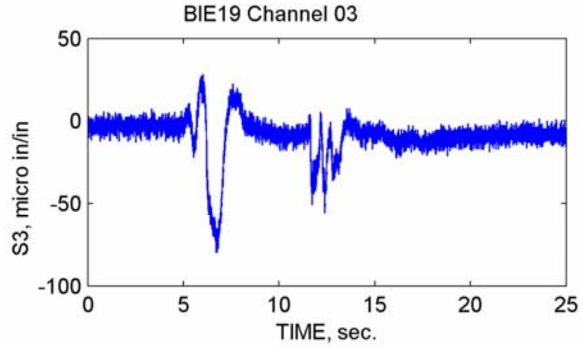

BIE17 Channel 38
AY3, g's
20
10
0
-10
-20
BIE17 Channel 39
AZ3, g's
BIE17 Channel 40
AX4, g's
0.1
0
-0.1
-0.2
-0.3
BIE17 Channel 41
AY4, g's
BIE17 Channel 42
AX5, g's
-0.08
-0.1
-0.12
-0.14
-0.16
BIE17 Channel 43
AY5, g's
0.02
0
-0.02
-0.04
-0.06
BIE17 Channel 44
AX6, g's
0.02
0.01
0
-0.01
-0.02
BIE17 Channel 45
AY6, g's
0.04
0.02
0
-0.02
0
5
10
15
20
25
TIME, sec.

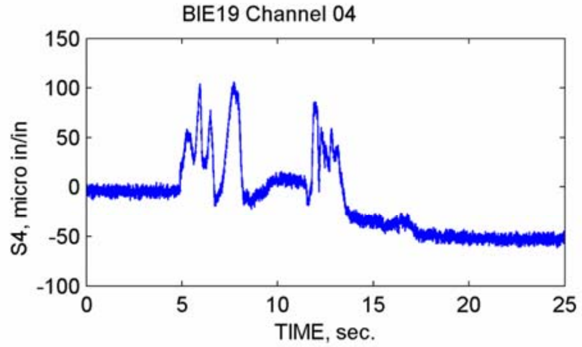

BIE17 Channel 46
x 10^-3
AX7, g's
5
0
-5
-10
TIME, sec.
0
5
10
15
20
25
BIE17 Channel 47
AY7, g's
0.015
0.01
0.005
0
-0.005
-0.01
TIME, sec.
BIE17 Channel 48
AX8, g's
0.05
0
-0.05
TIME, sec.
BIE17 Channel 49
AY8, g's
0.02
0.01
0
-0.01
-0.02
TIME, sec.
BIE17 Channel 50
AX9, g's
0.01
0.005
0
-0.005
-0.01
-0.015
TIME, sec.
BIE17 Channel 51
AY9, g's
0.01
0.005
0
-0.005
-0.01
TIME, sec.
BIE17 Channel 52
AX10, g's
0.04
0.02
0
-0.02
-0.04
TIME, sec.
BIE17 Channel 53
AY10, g's
0.01
0.005
0
-0.005
-0.01
TIME, sec.

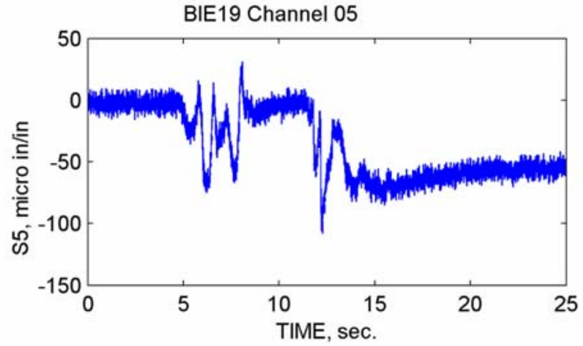

BIE17 Channel 54
AX11, g's
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20
25
TIME, sec.
BIE17 Channel 55
AY11, g's
0.02
0.01
0
-0.01
-0.02
0
5
10
15
20
25
TIME, sec.
BIE17 Channel 56
Trigger Signal, Volts
6
4
2
0
-2
0
5
10
15
20
25
TIME, sec.

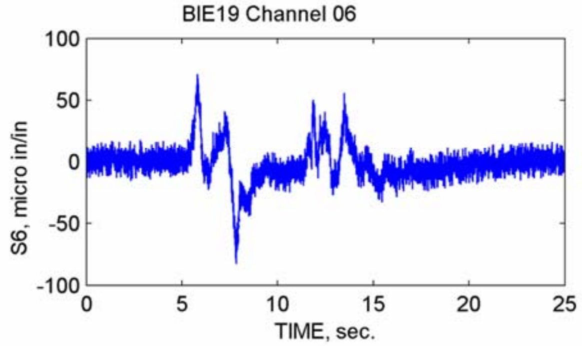

BIE19 Channel 01
200
100
0
-100
-200
S1, micro in/in
0
5
10
15
20
25
TIME, sec.

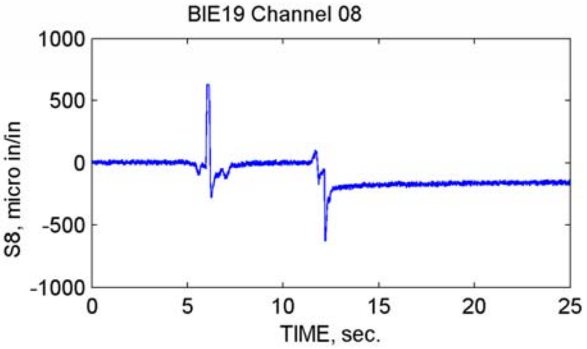

BIE19 Channel 02
300
200
100
0
-100
S2, micro in/in
0
5
10
15
20
25
TIME, sec.

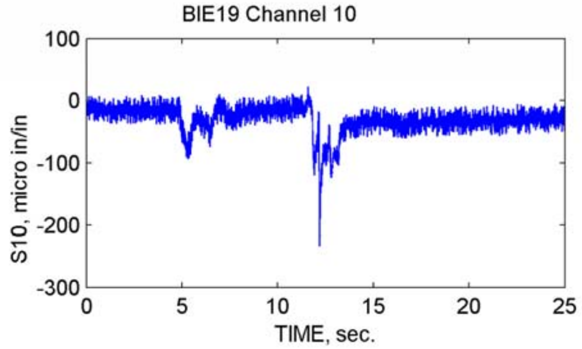

BIE19 Channel 03
50
0
-50
-100
S3, micro in/in
0
5
10
15
20
25
TIME, sec.


BIE19 Channel 04
150
100
50
0
-50
-100
S4, micro in/in
0
5
10
15
20
25
TIME, sec.

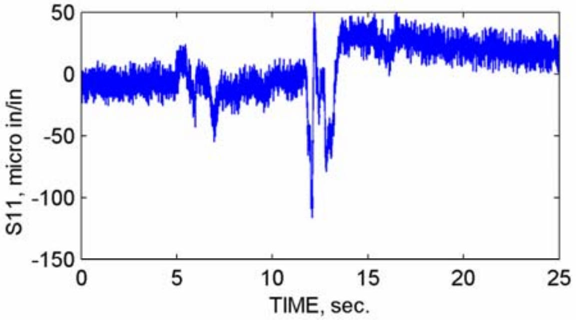

BIE19 Channel 05
50
0
-50
-100
-150
S5, micro in/in
0
5
10
15
20
25
TIME, sec.


BIE19 Channel 06
100
50
0
-50
-100
S6, micro in/in
0
5
10
15
20
25
TIME, sec.

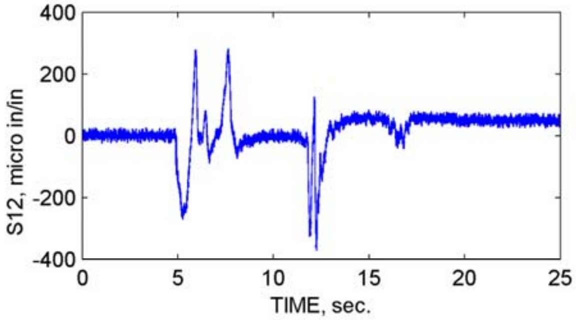

BIE19 Channel 08
1000
500
0
-500
-1000
S8, micro in/in
0
5
10
15
20
25
TIME, sec.


BIE19 Channel 10
100
0
-100
-200
-300
S10, micro in/in
0
5
10
15
20
25
TIME, sec.

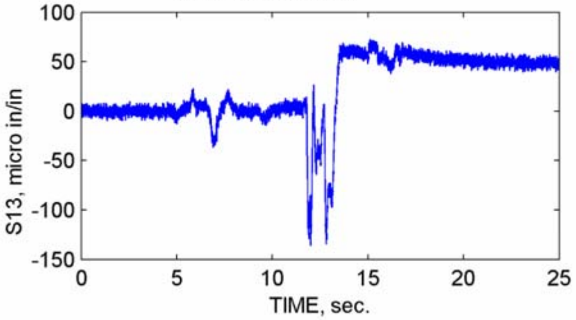
BIE19 Channel 11



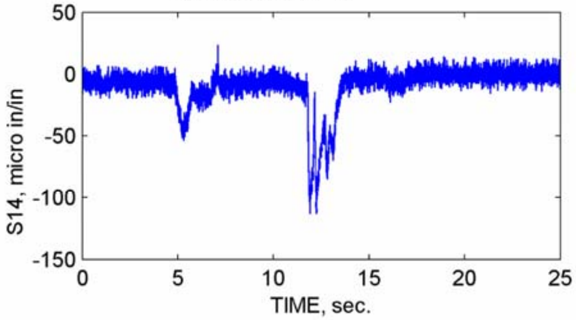
BIE19 Channel 12



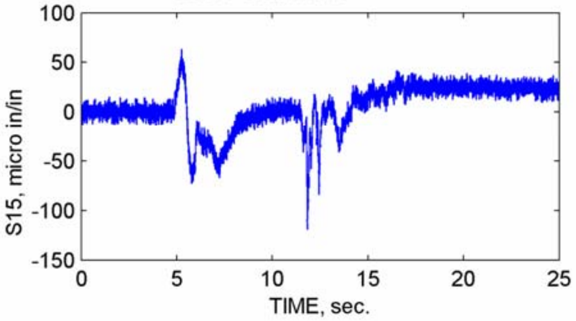
BIE19 Channel 13



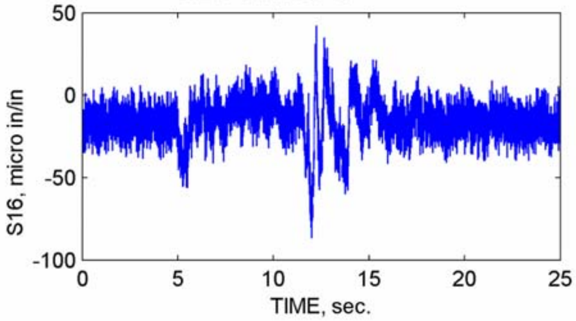
BIE19 Channel 14



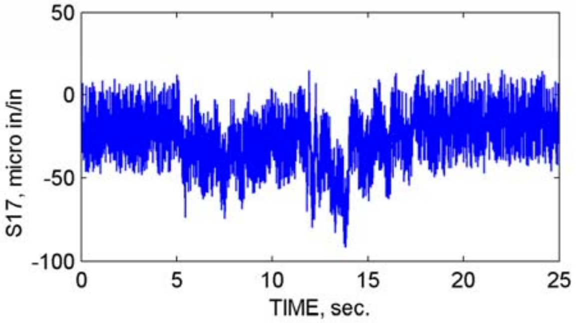
BIE19 Channel 15



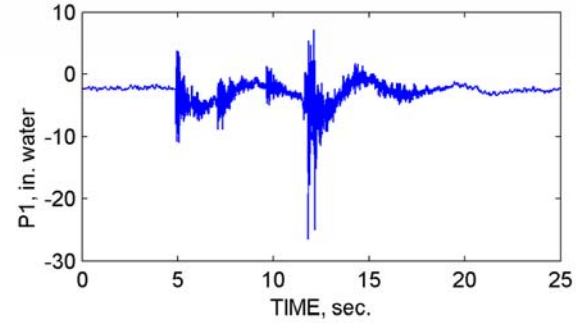
BIE19 Channel 16

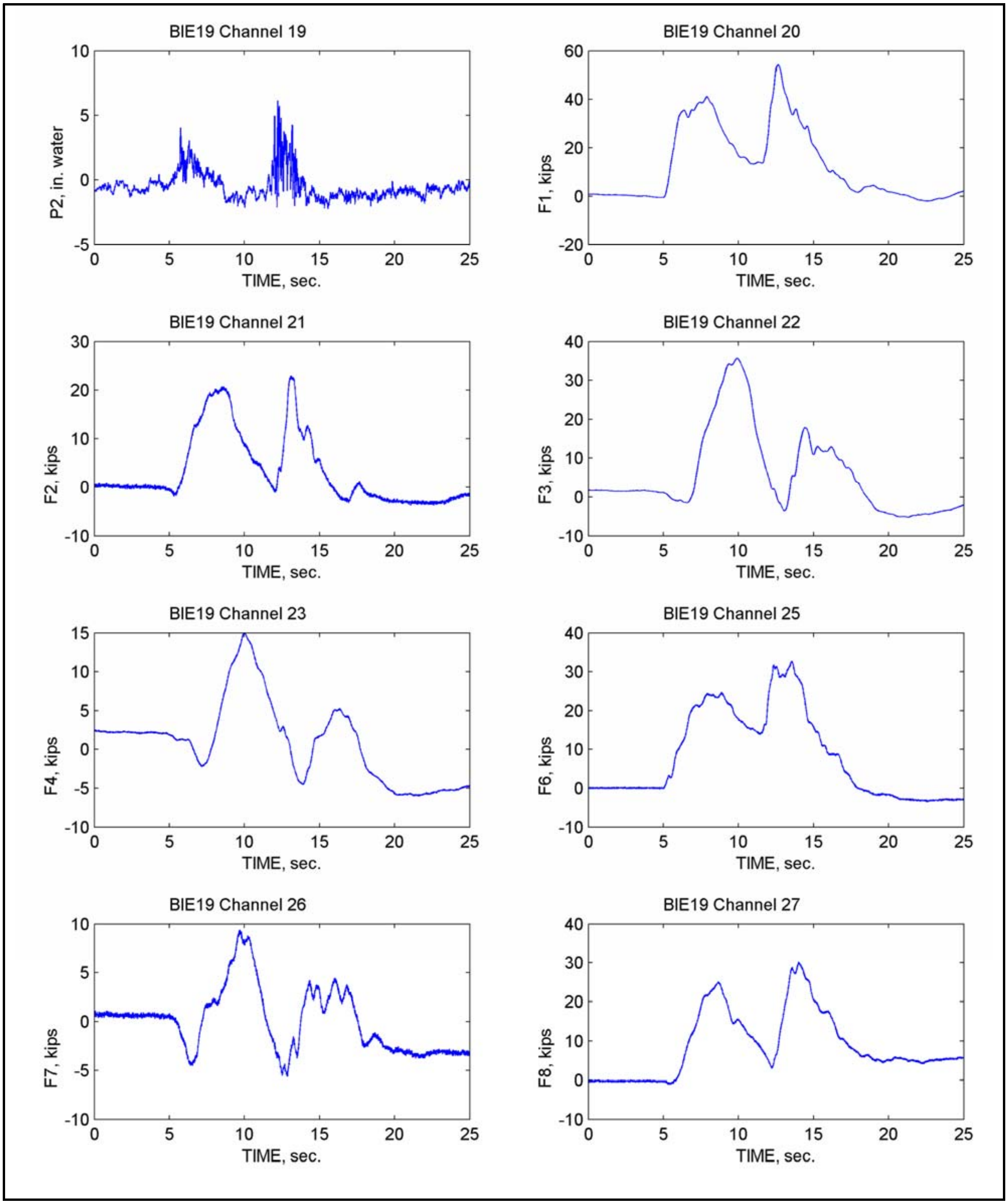


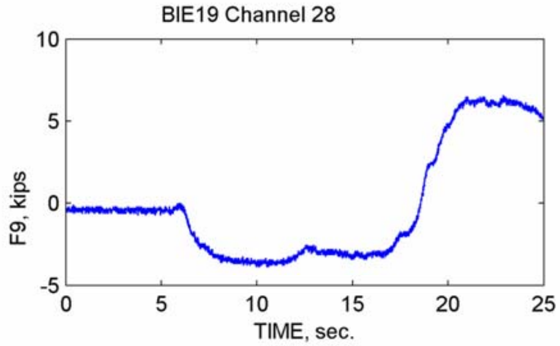
BIE19 Channel 17

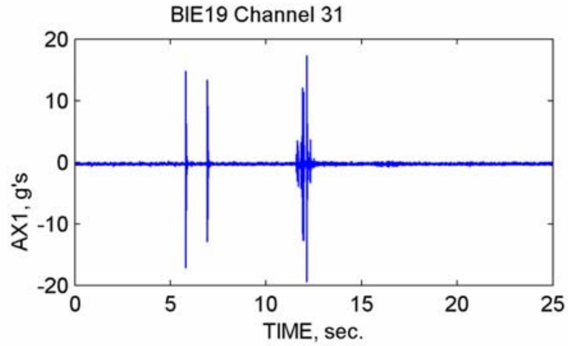


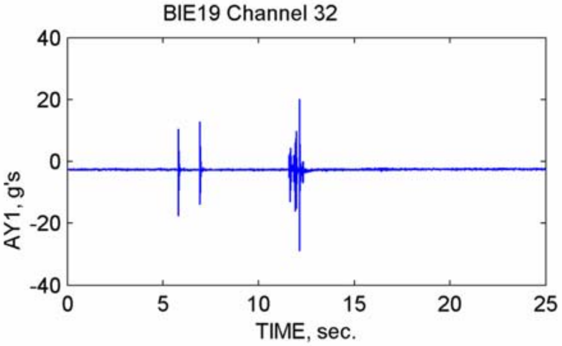
BIE19 Channel 18

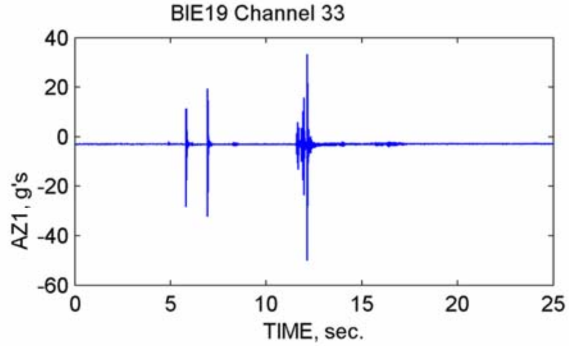


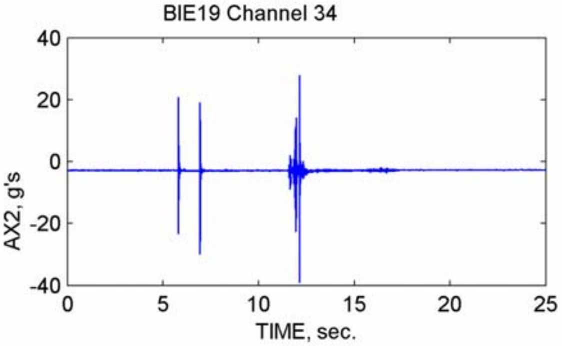

BIE19 Channel 19
P2, in. water
10
5
0
-5
TIME, sec.
0
5
10
15
20
25
BIE19 Channel 20
F1, kips
60
40
20
0
-20
TIME, sec.
BIE19 Channel 21
F2, kips
30
20
10
0
-10
TIME, sec.
BIE19 Channel 22
F3, kips
40
30
20
10
0
-10
TIME, sec.
BIE19 Channel 23
F4, kips
15
10
5
0
-5
-10
TIME, sec.
BIE19 Channel 25
F6, kips
40
30
20
10
0
-10
TIME, sec.
BIE19 Channel 26
F7, kips
10
5
0
-5
-10
TIME, sec.
BIE19 Channel 27
F8, kips
40
30
20
10
0
-10
TIME, sec.

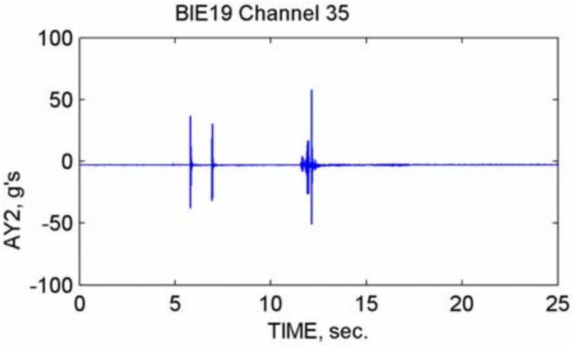

BIE19 Channel 28

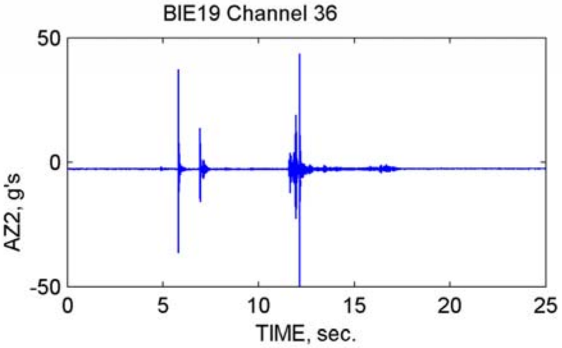

BIE19 Channel 31

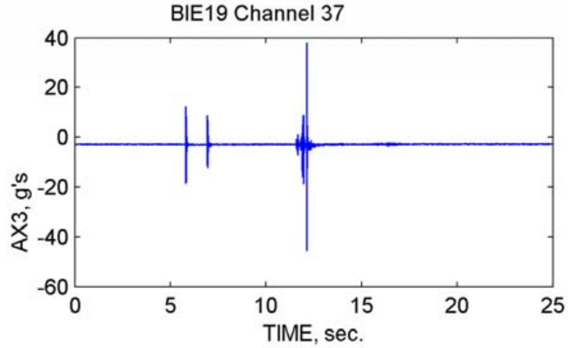

BIE19 Channel 32

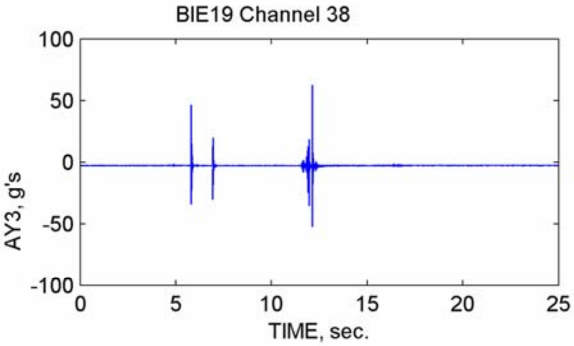

BIE19 Channel 33

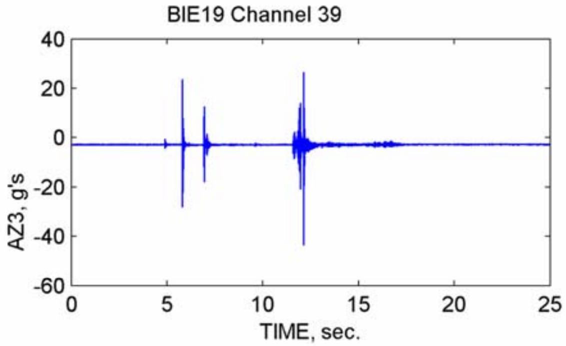

BIE19 Channel 34

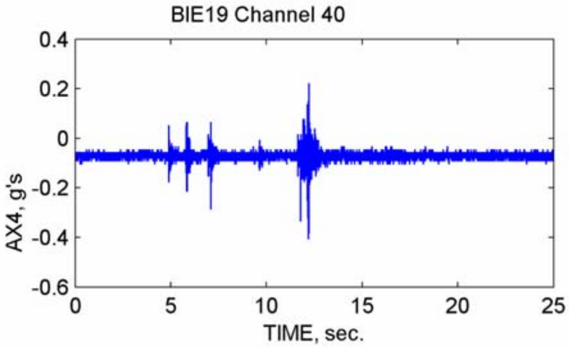

BIE19 Channel 35

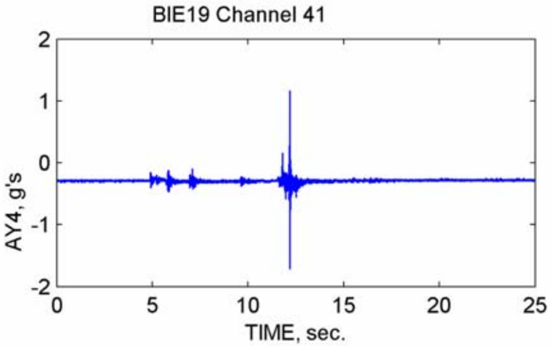

BIE19 Channel 36

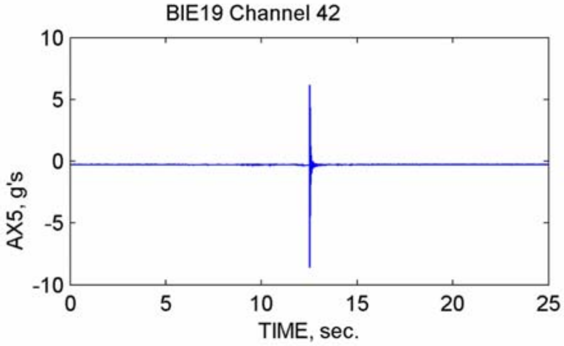

BIE19 Channel 37

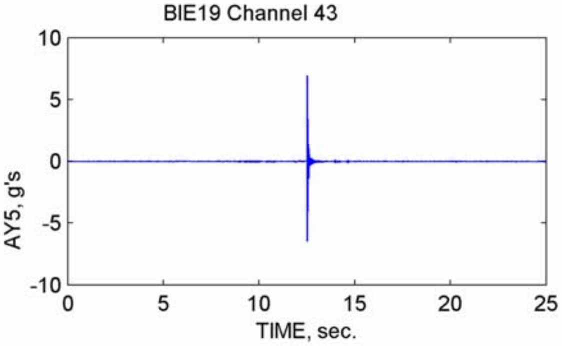

BIE19 Channel 38

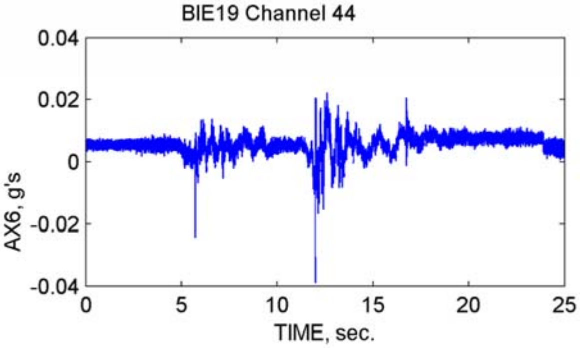

BIE19 Channel 39

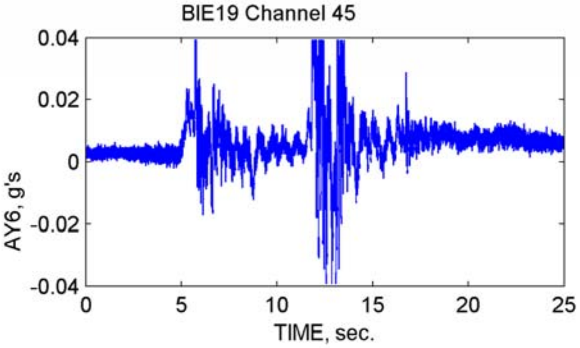

BIE19 Channel 40

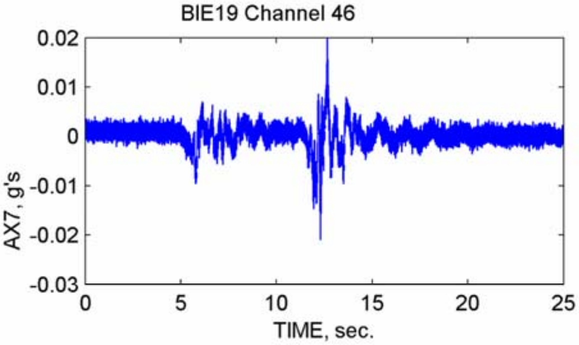

BIE19 Channel 41

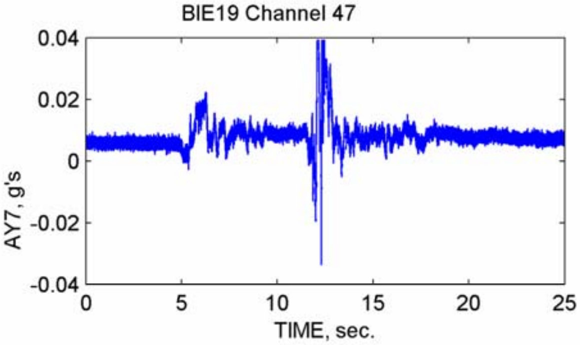

BIE19 Channel 42

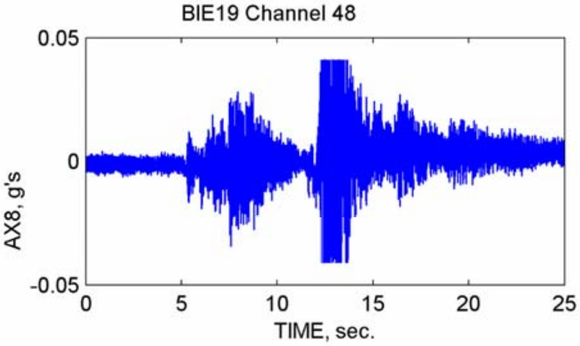

BIE19 Channel 43

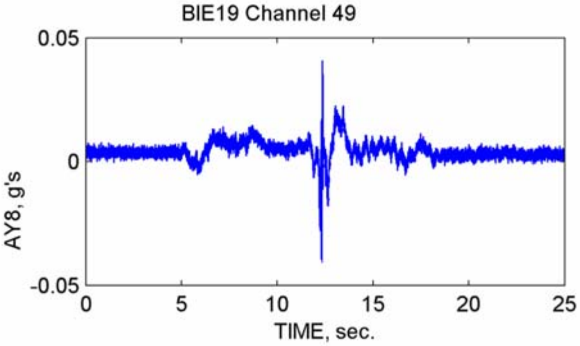

BIE19 Channel 44

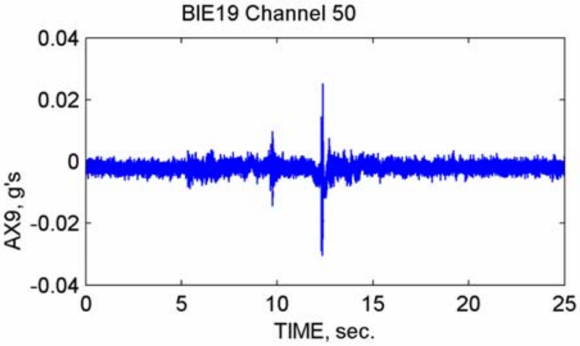

BIE19 Channel 45

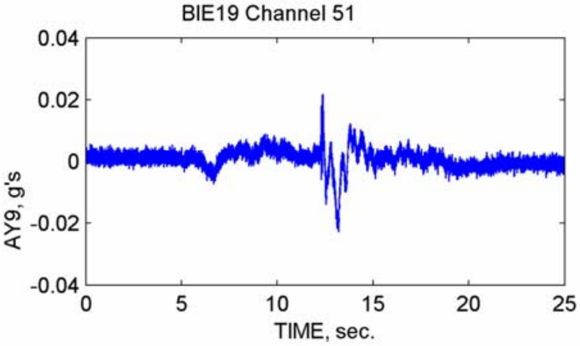

BIE19 Channel 46

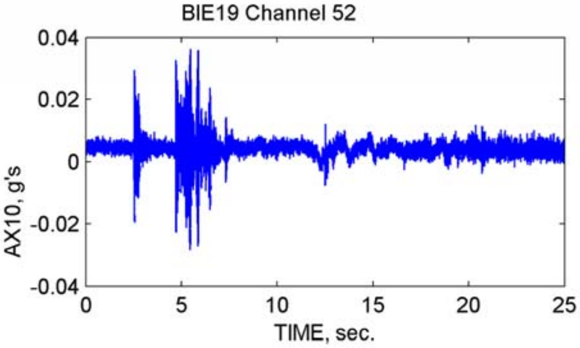

BIE19 Channel 47

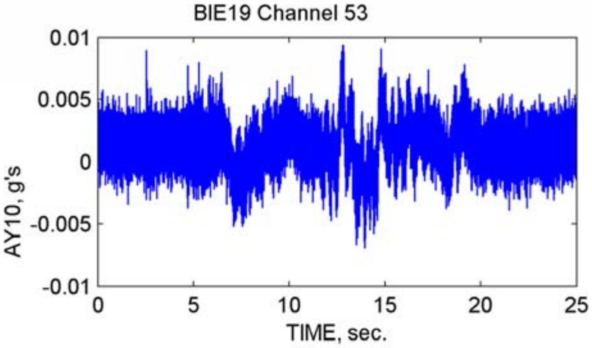

BIE19 Channel 48

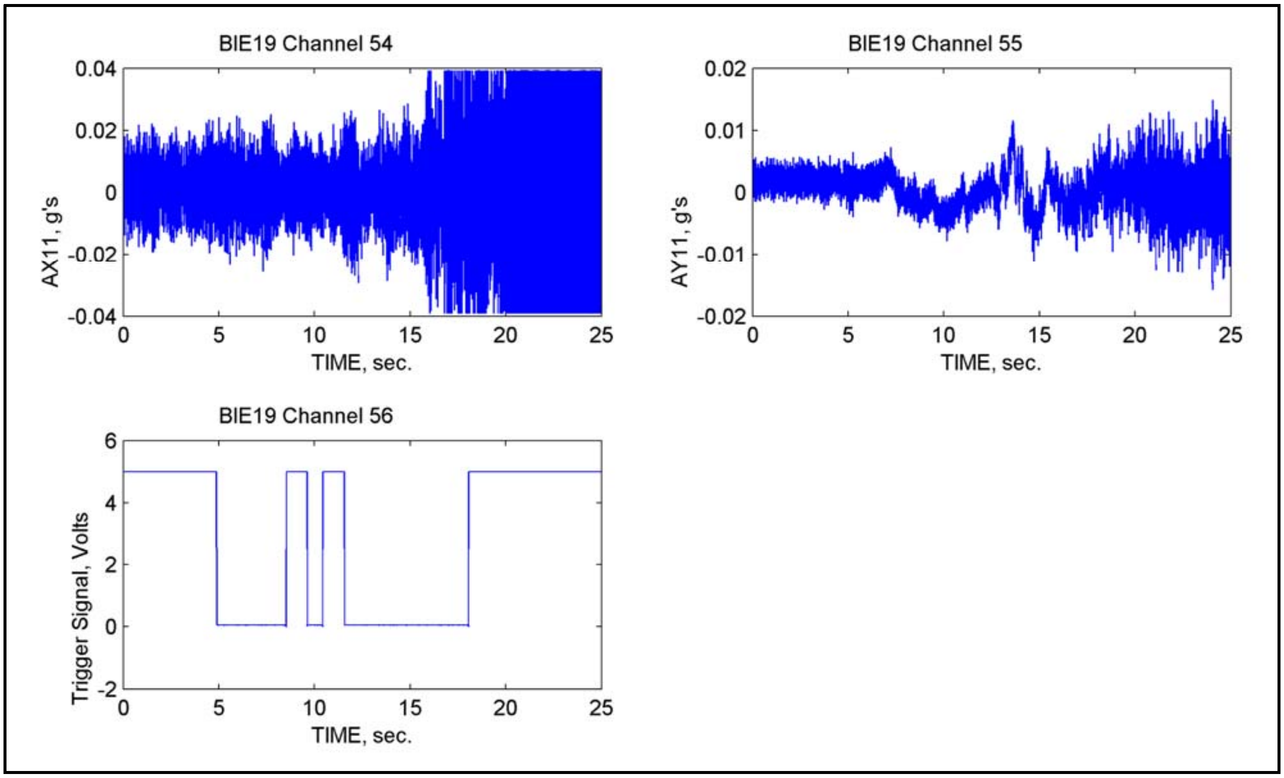

BIE19 Channel 49

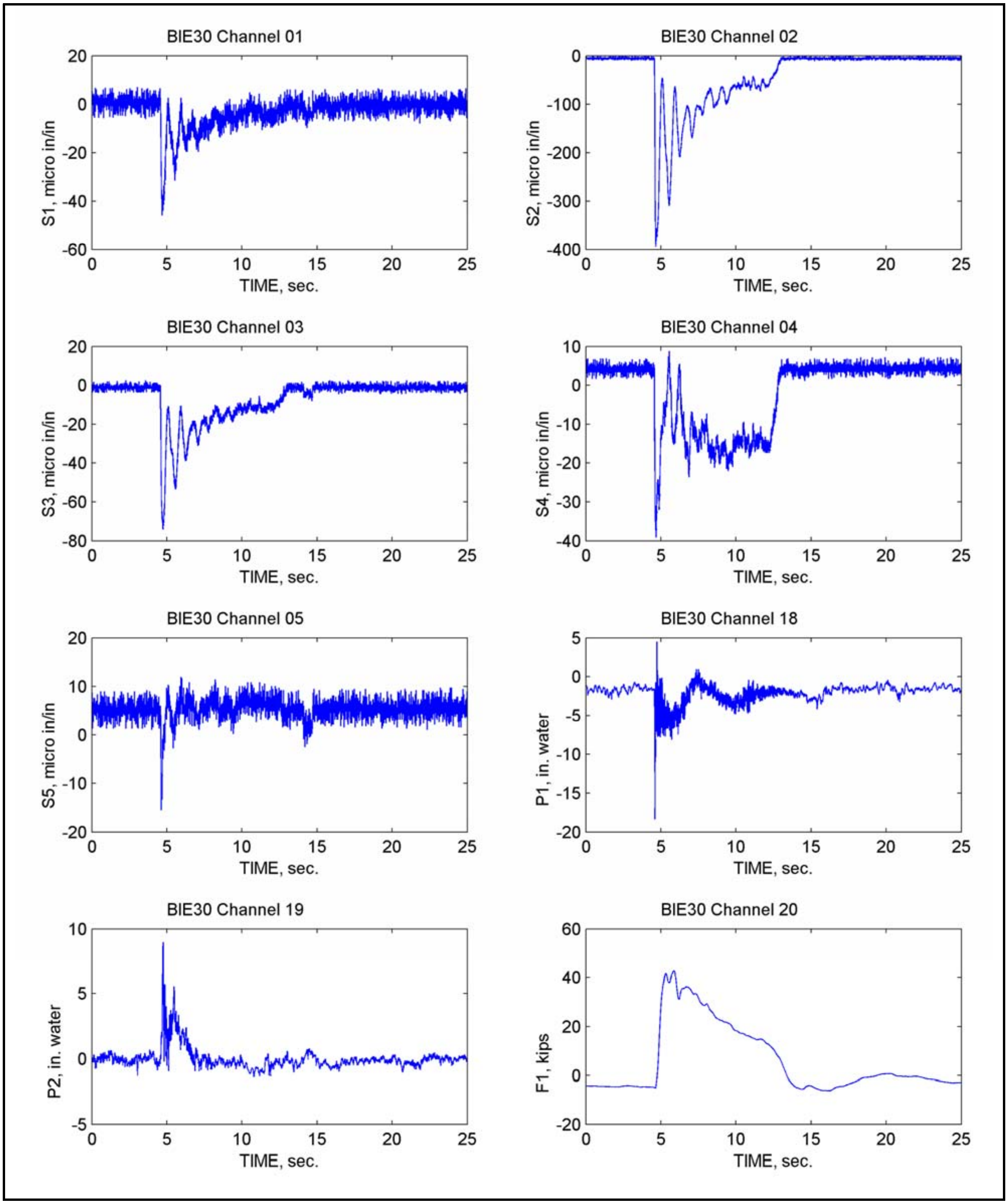

BIE19 Channel 50


BIE19 Channel 51

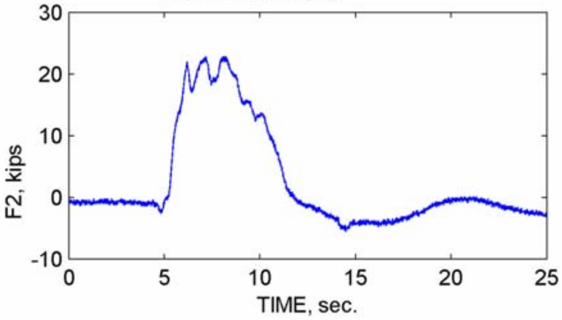

BIE19 Channel 52


BIE19 Channel 53

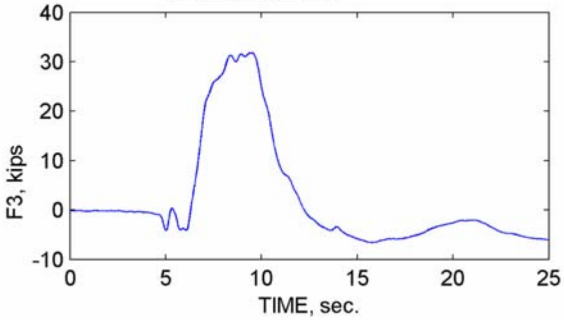

BIE19 Channel 54
AX11, g's
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20
25
TIME, sec.
BIE19 Channel 55
AY11, g's
0.02
0.01
0
-0.01
-0.02
0
5
10
15
20
25
TIME, sec.
BIE19 Channel 56
Trigger Signal, Volts
6
4
2
0
-2
0
5
10
15
20
25
TIME, sec.


BIE30 Channel 01
S1, micro in/in
20
0
-20
-40
-60
0
5
10
15
20
25
TIME, sec.
BIE30 Channel 02
S2, micro in/in
0
-100
-200
-300
-400
0
5
10
15
20
25
TIME, sec.
BIE30 Channel 03
S3, micro in/in
20
0
-20
-40
-60
-80
0
5
10
15
20
25
TIME, sec.
BIE30 Channel 04
S4, micro in/in
10
0
-10
-20
-30
-40
0
5
10
15
20
25
TIME, sec.
BIE30 Channel 05
S5, micro in/in
20
10
0
-10
-20
0
5
10
15
20
25
TIME, sec.
BIE30 Channel 18
P1, in. water
5
0
-5
-10
-15
-20
0
5
10
15
20
25
TIME, sec.
BIE30 Channel 19
P2, in. water
10
5
0
-5
0
5
10
15
20
25
TIME, sec.
BIE30 Channel 20
F1, kips
60
40
20
0
-20
0
5
10
15
20
25
TIME, sec.

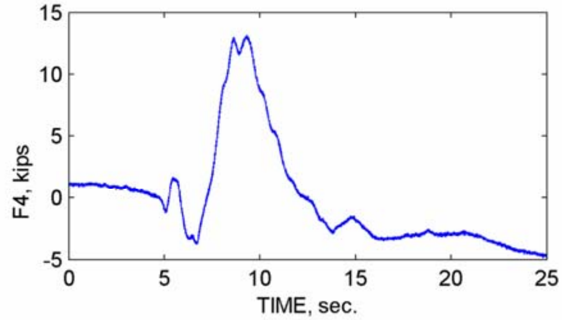
BIE30 Channel 21



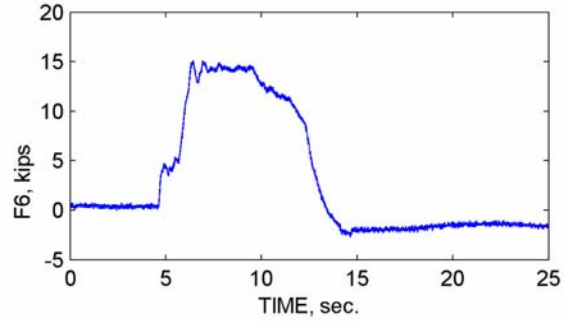
BIE30 Channel 22



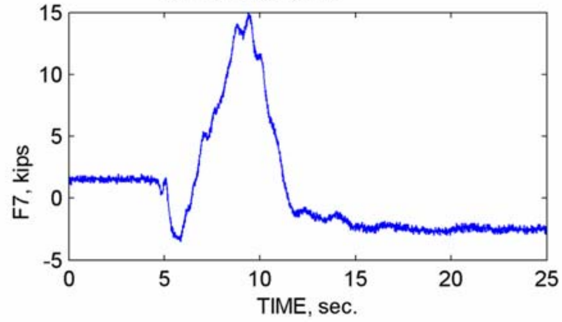
BIE30 Channel 23



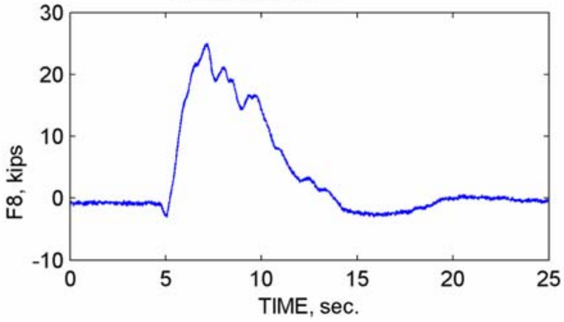
BIE30 Channel 25



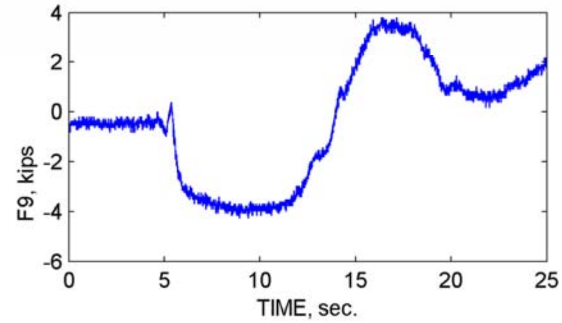
BIE30 Channel 26



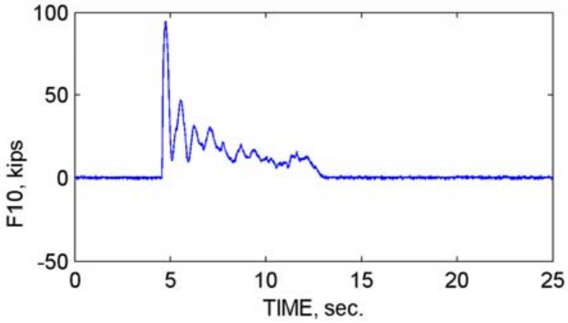
BIE30 Channel 27

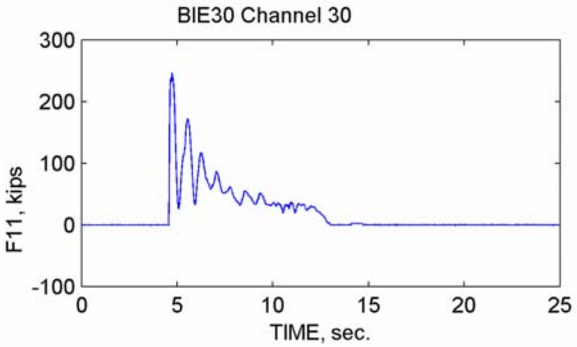


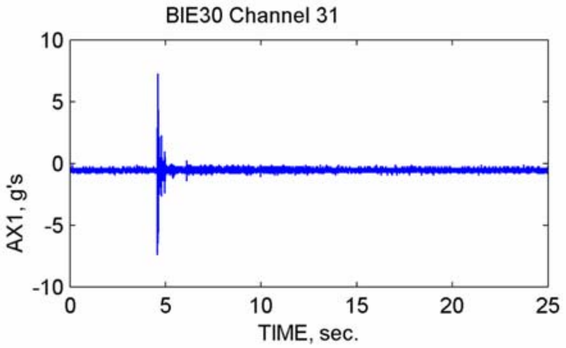
BIE30 Channel 28

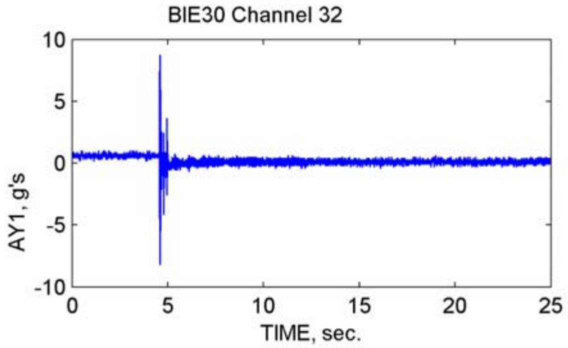


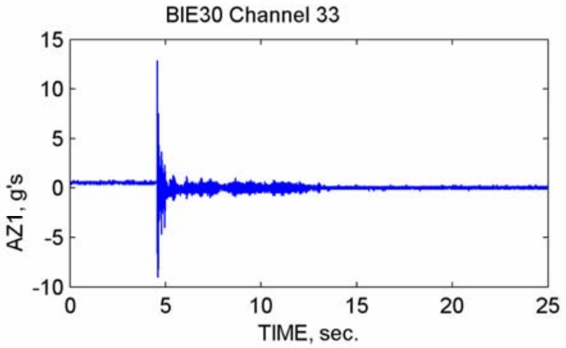
BIE30 Channel 29

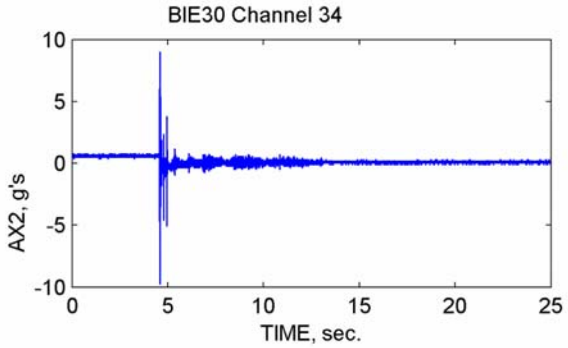


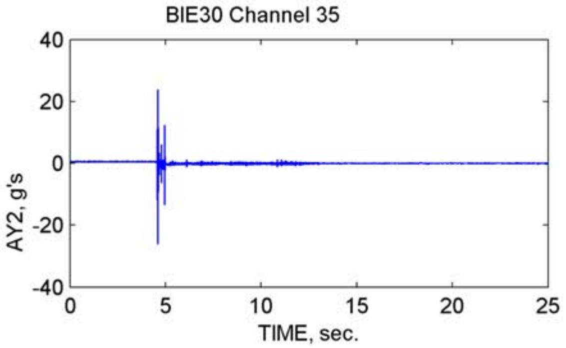

BIE30 Channel 30
F11, kips
300
200
100
0
-100
0
5
10
15
20
25
TIME, sec.

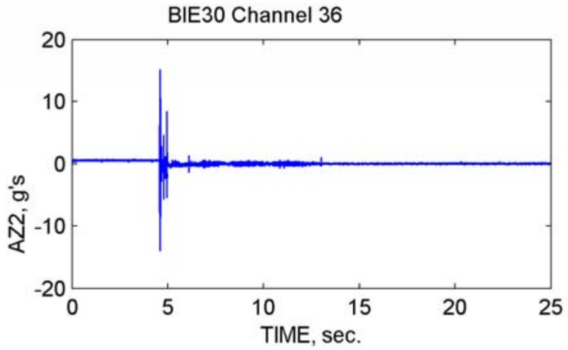

BIE30 Channel 31
AX1, g's
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.

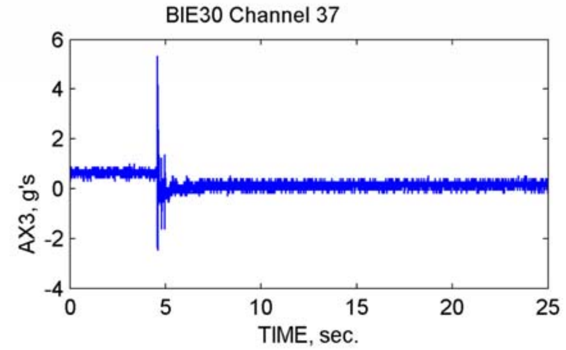

BIE30 Channel 32
AY1, g's
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.

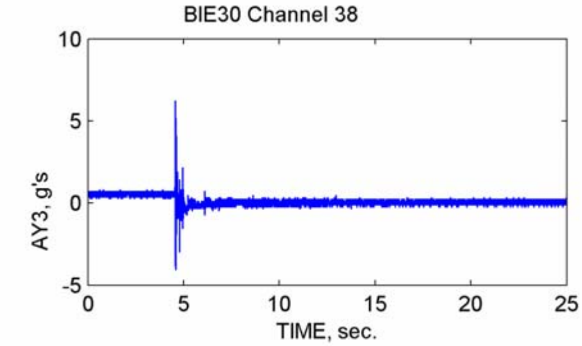

BIE30 Channel 33
AZ1, g's
15
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.

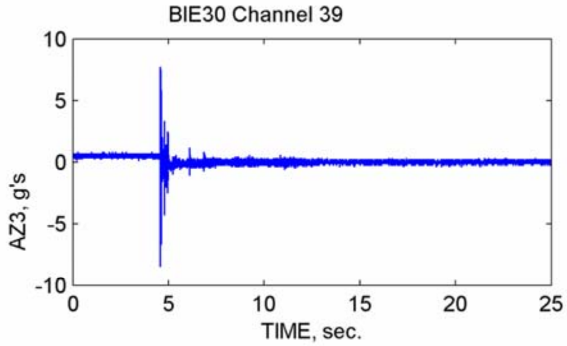

BIE30 Channel 34
AX2, g's
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.

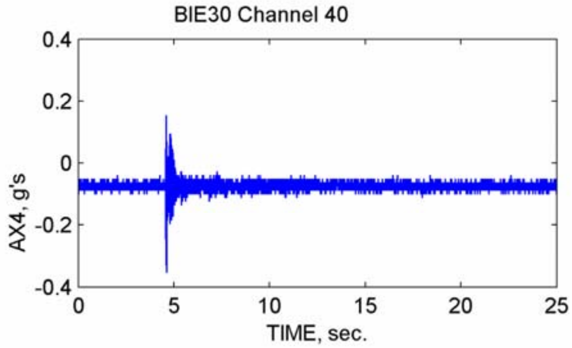

BIE30 Channel 35
AY2, g's
40
20
0
-20
-40
0
5
10
15
20
25
TIME, sec.

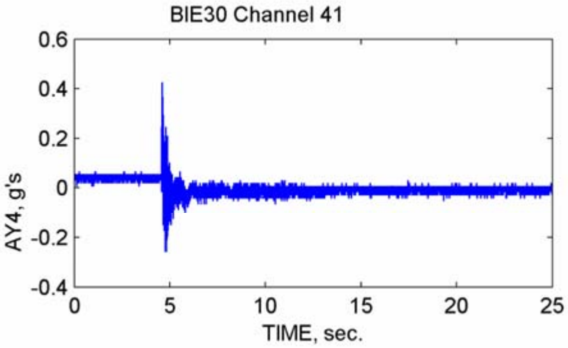

BIE30 Channel 36
AZ2, g's
20
10
0
-10
-20
0
5
10
15
20
25
TIME, sec.

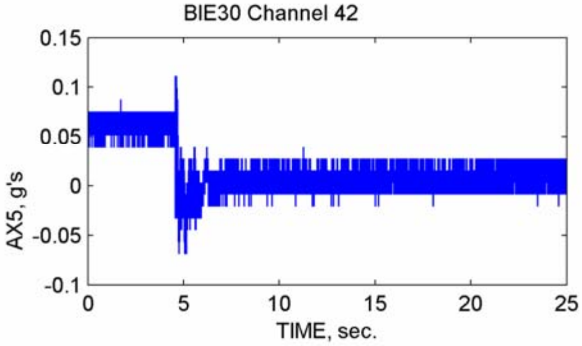

BIE30 Channel 37
AX3, g's
6
4
2
0
-2
-4
0
5
10
15
20
25
TIME, sec.

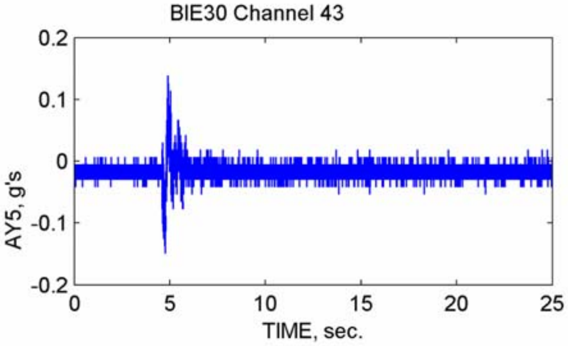

BIE30 Channel 38
AY3, g's
10
5
0
-5
0
5
10
15
20
25
TIME, sec.

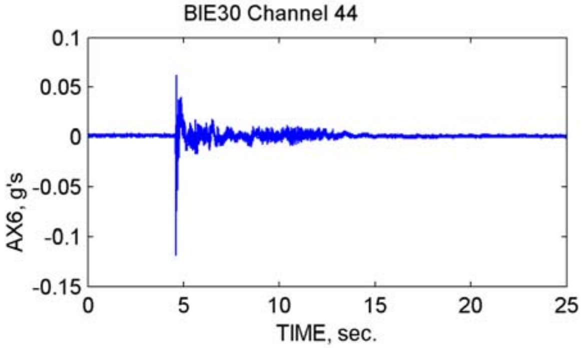

BIE30 Channel 39
AZ3, g's
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.

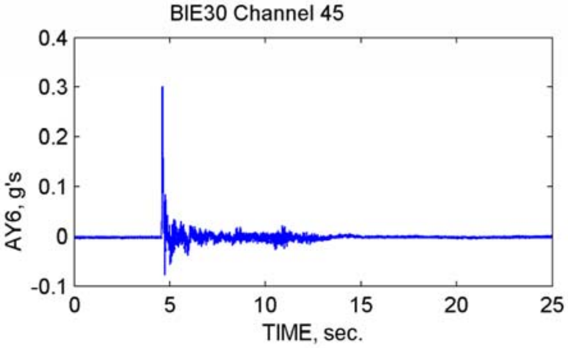

BIE30 Channel 40
AX4, g's
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
TIME, sec.

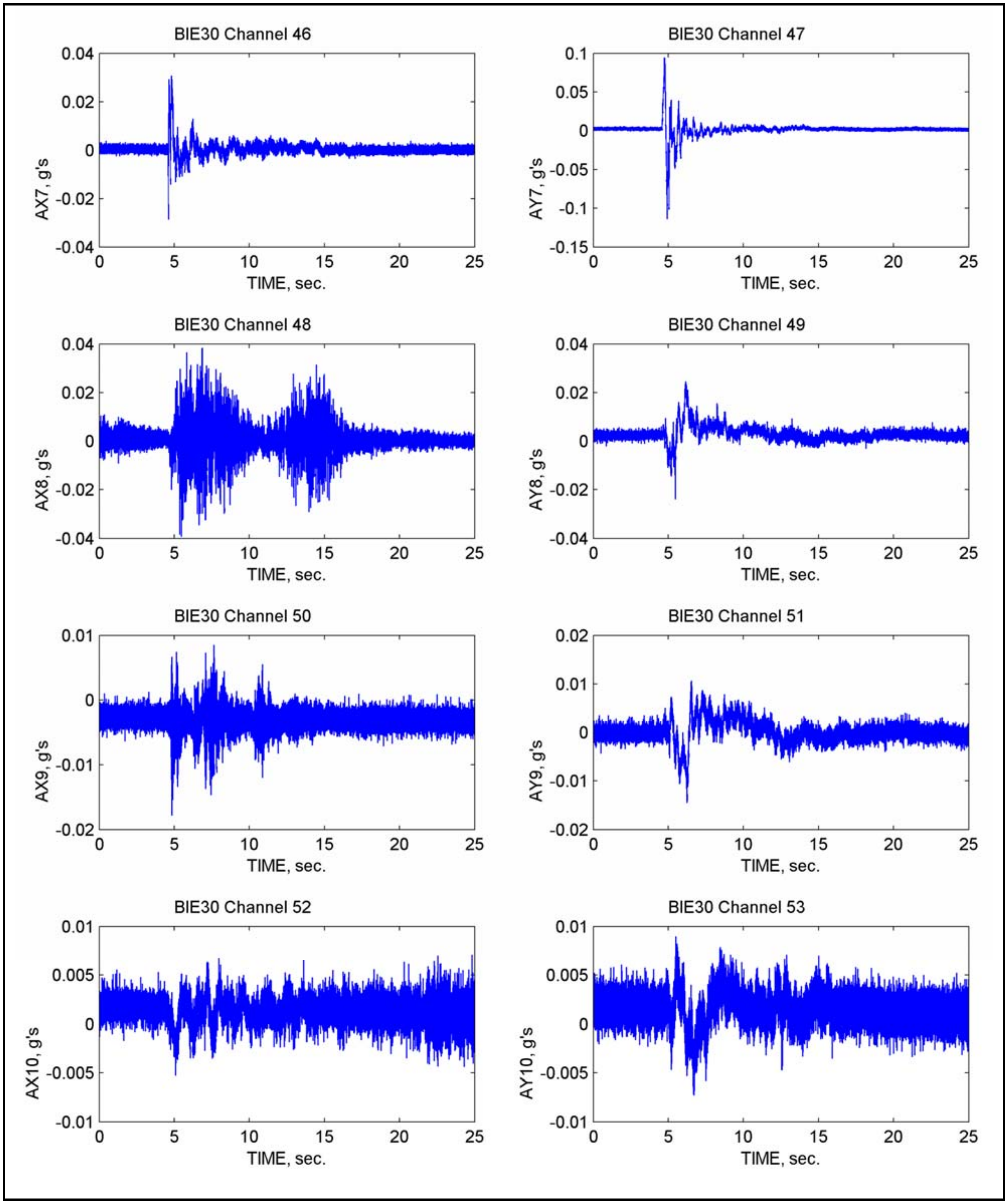

BIE30 Channel 41
AY4, g's
0.6
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
TIME, sec.

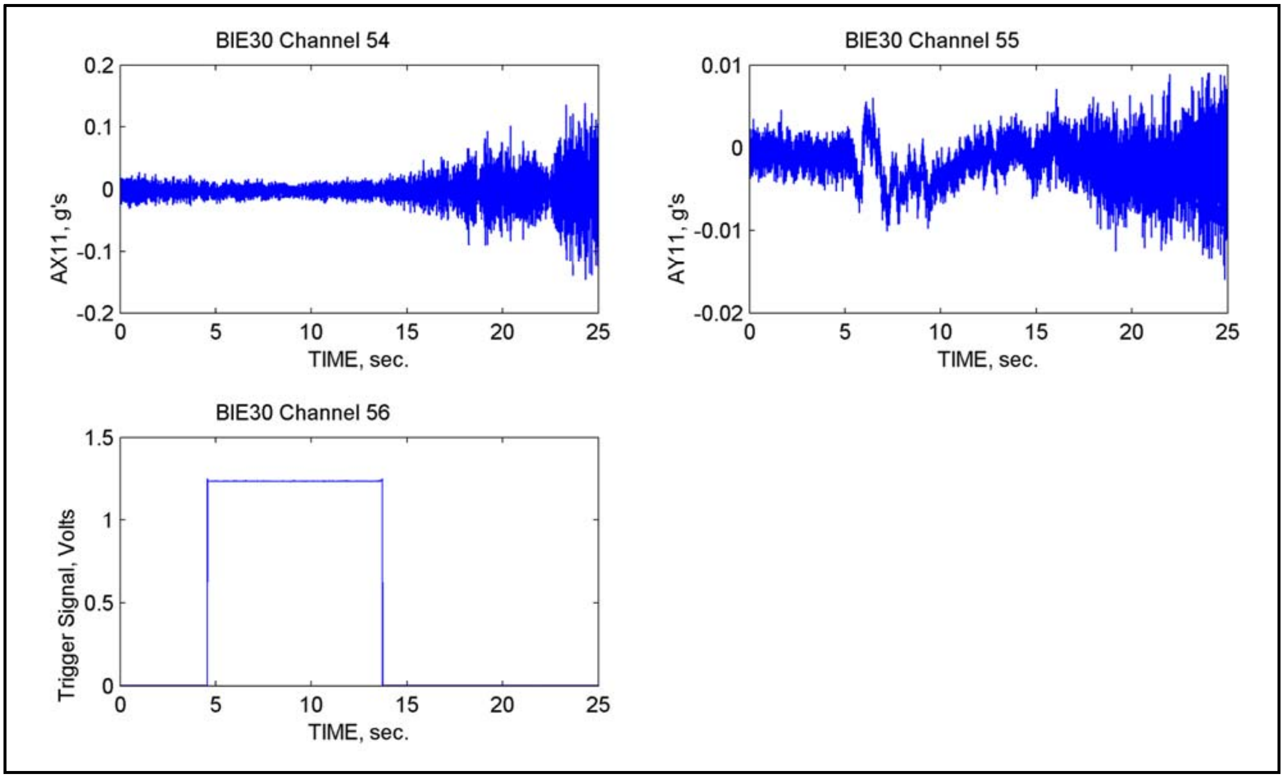

BIE30 Channel 42
AX5, g's
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
TIME, sec.


BIE30 Channel 43
AY5, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.


BIE30 Channel 44
AX6, g's
0.1
0.05
0
-0.05
-0.1
-0.15
0
5
10
15
20
25
TIME, sec.

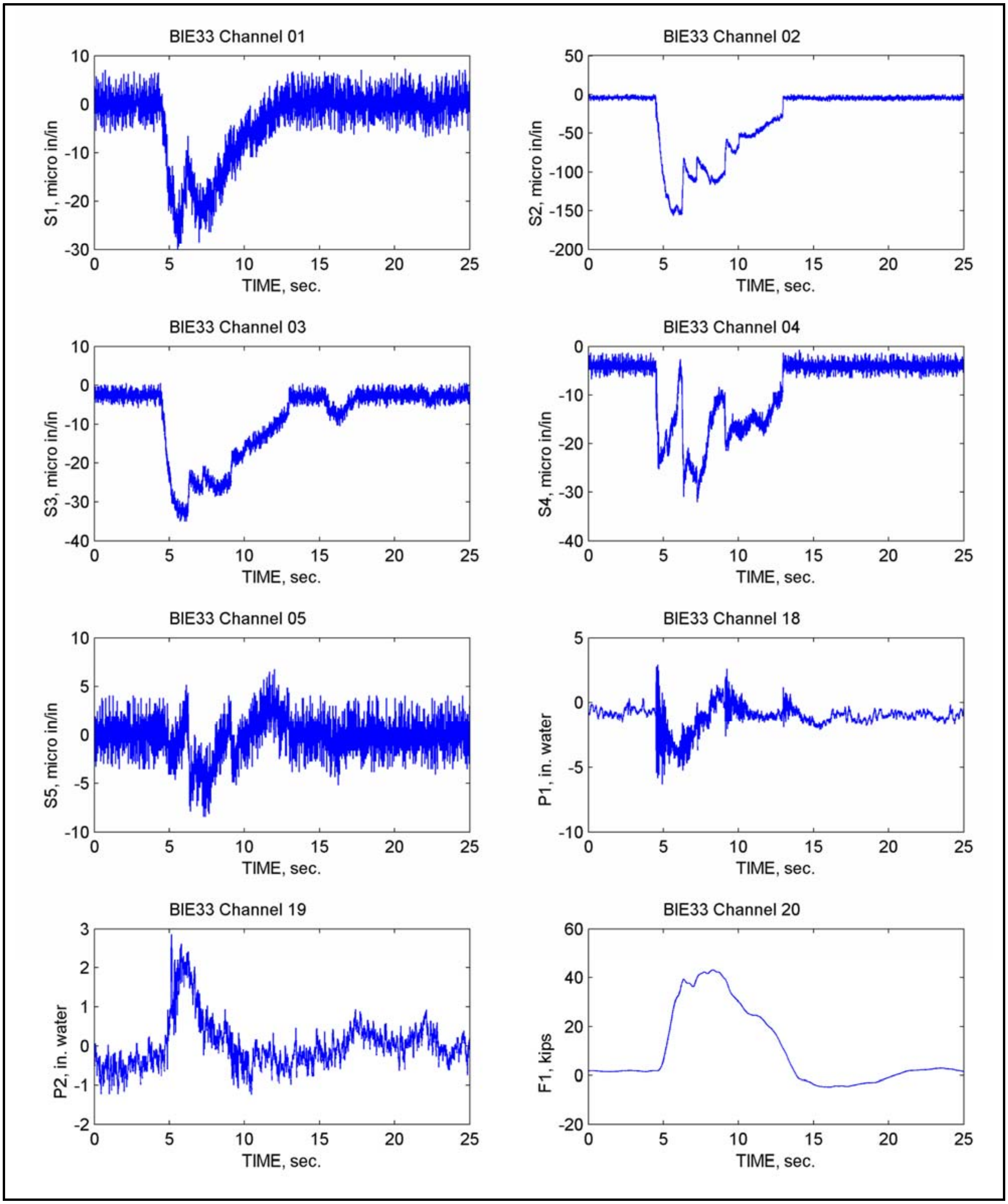

BIE30 Channel 45
AY6, g's
0.4
0.3
0.2
0.1
0
-0.1
0
5
10
15
20
25
TIME, sec.

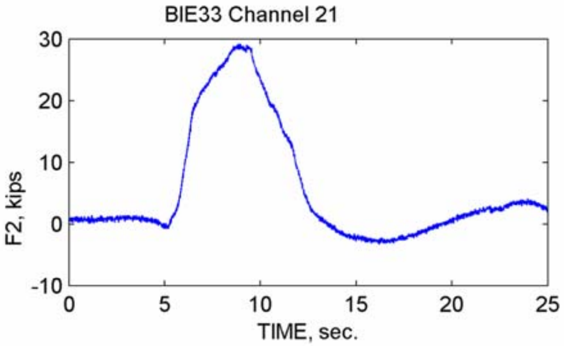

BIE30 Channel 46
AX7, g's
0.04
0.02
0
-0.02
-0.04
BIE30 Channel 47
AY7, g's
0.1
0.05
0
-0.05
-0.1
-0.15
BIE30 Channel 48
AX8, g's
0.04
0.02
0
-0.02
-0.04
BIE30 Channel 49
AY8, g's
0.04
0.02
0
-0.02
-0.04
BIE30 Channel 50
AX9, g's
0.01
0
-0.01
-0.02
BIE30 Channel 51
AY9, g's
0.02
0.01
0
-0.01
-0.02
BIE30 Channel 52
AX10, g's
0.01
0.005
0
-0.005
-0.01
BIE30 Channel 53
AY10, g's
0.01
0.005
0
-0.005
-0.01
0
5
10
15
20
25
TIME, sec.

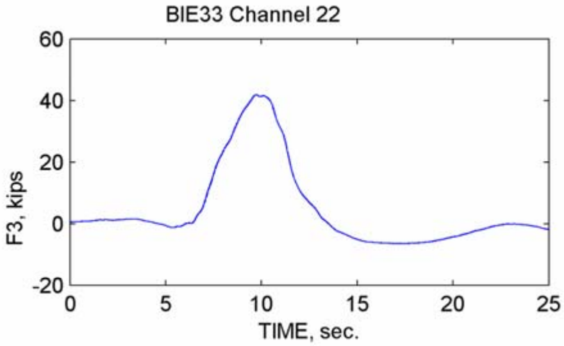

BIE30 Channel 54

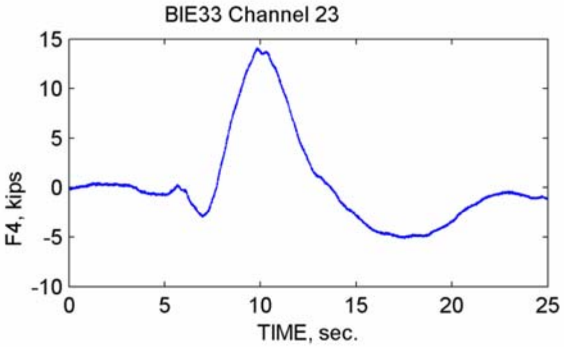
BIE30 Channel 55

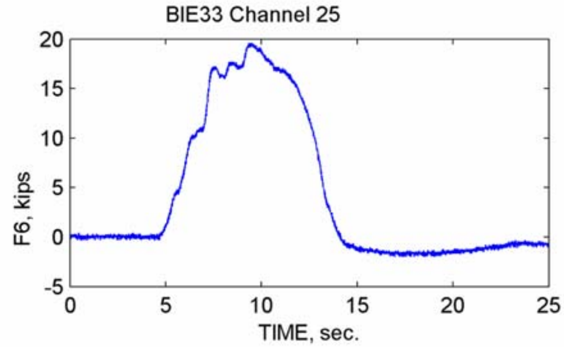
BIE30 Channel 56

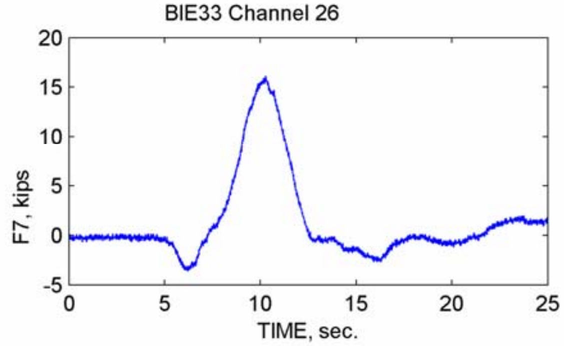

BIE33 Channel 01
S1, micro in/in
10
0
-10
-20
-30
0
5
10
15
20
25
TIME, sec.
BIE33 Channel 02
S2, micro in/in
50
0
-50
-100
-150
-200
0
5
10
15
20
25
TIME, sec.
BIE33 Channel 03
S3, micro in/in
10
0
-10
-20
-30
-40
0
5
10
15
20
25
TIME, sec.
BIE33 Channel 04
S4, micro in/in
0
-10
-20
-30
-40
0
5
10
15
20
25
TIME, sec.
BIE33 Channel 05
S5, micro in/in
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.
BIE33 Channel 18
P1, in. water
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.
BIE33 Channel 19
P2, in. water
3
2
1
0
-1
-2
0
5
10
15
20
25
TIME, sec.
BIE33 Channel 20
F1, kips
60
40
20
0
-20
0
5
10
15
20
25
TIME, sec.

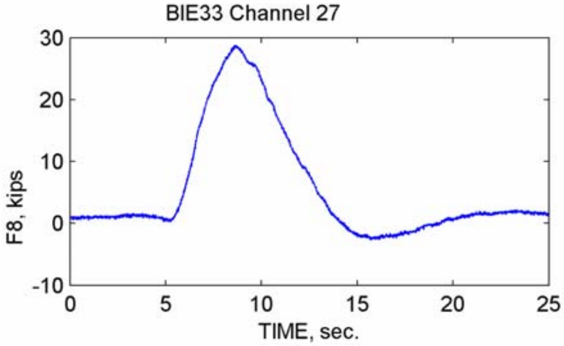

BIE33 Channel 21
F2, kips
30
20
10
0
-10
0
5
10
15
20
25
TIME, sec.

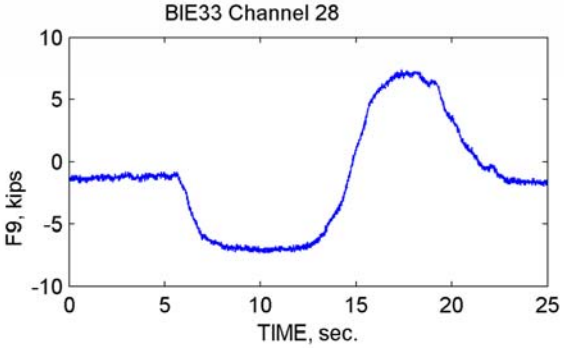

BIE33 Channel 22
F3, kips
60
40
20
0
-20
0
5
10
15
20
25
TIME, sec.

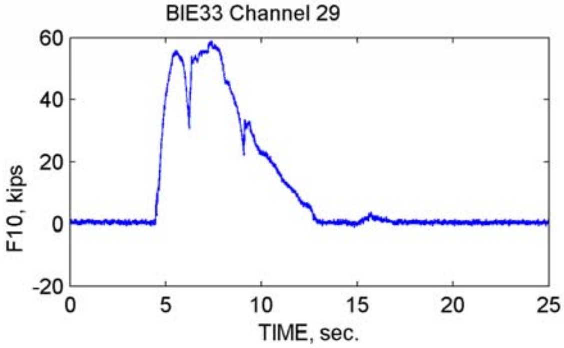

BIE33 Channel 23
F4, kips
15
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.

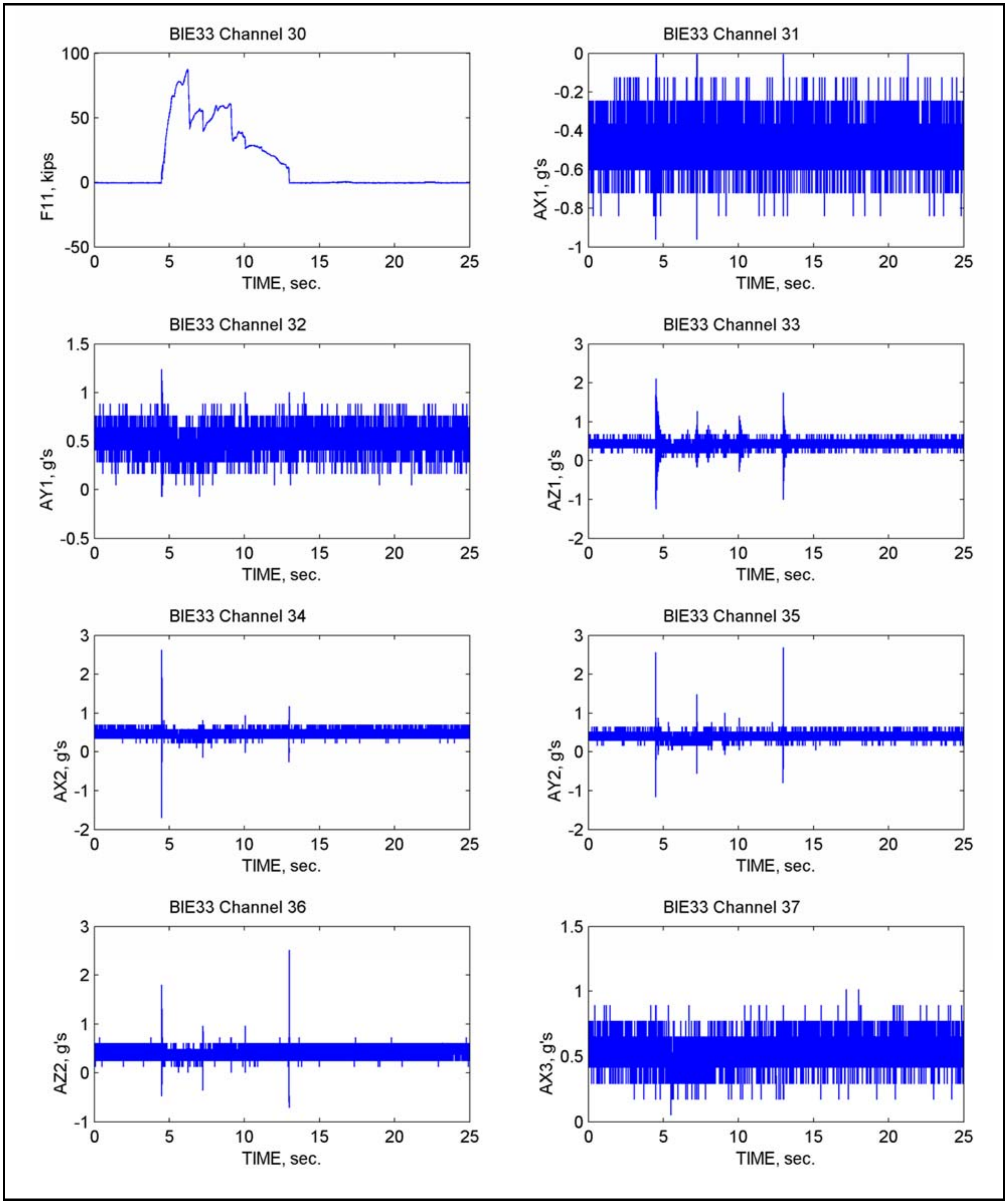

BIE33 Channel 25
F6, kips
20
15
10
5
0
-5
0
5
10
15
20
25
TIME, sec.

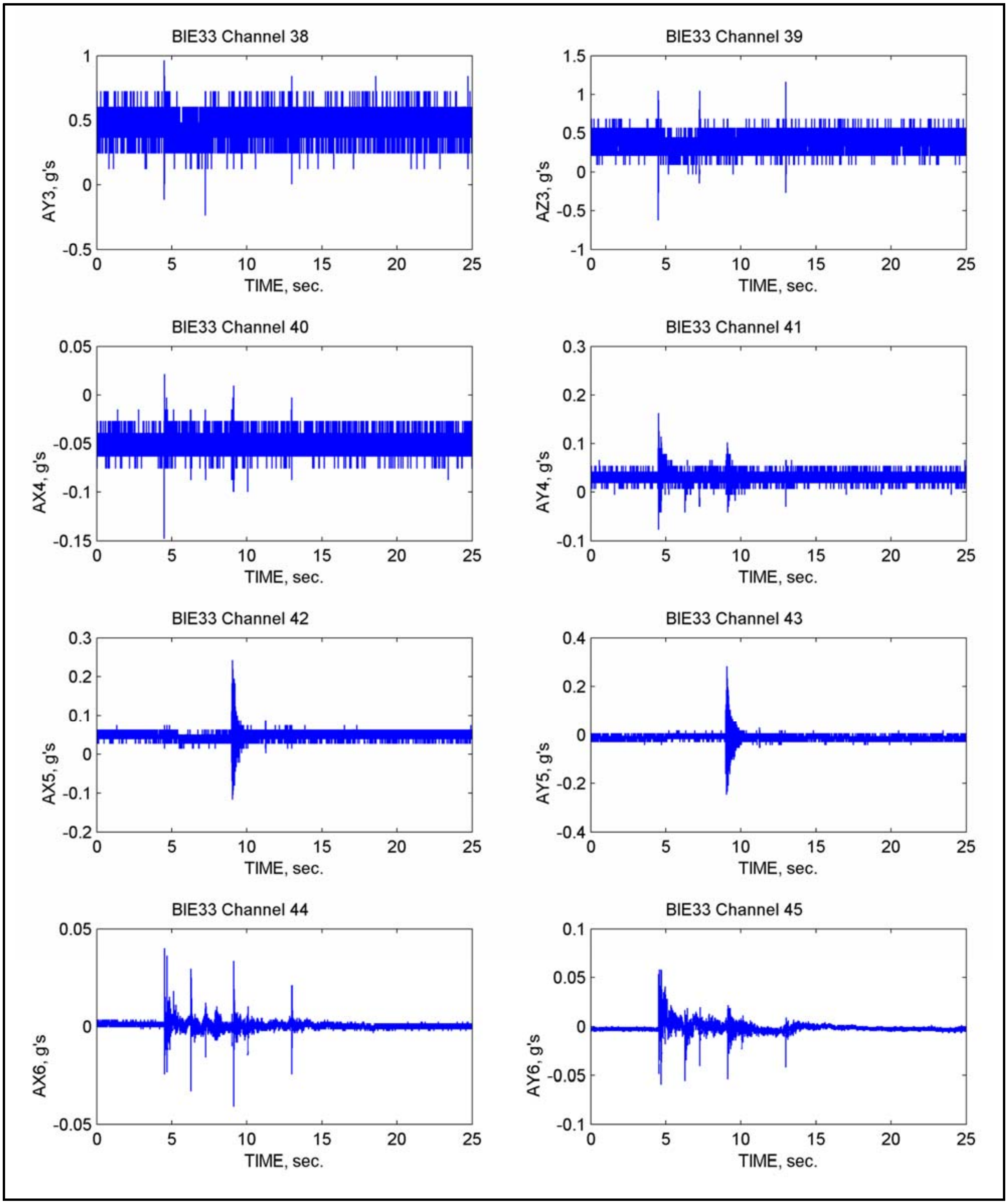

BIE33 Channel 26
F7, kips
20
15
10
5
0
-5
0
5
10
15
20
25
TIME, sec.


BIE33 Channel 27
F8, kips
30
20
10
0
-10
0
5
10
15
20
25
TIME, sec.

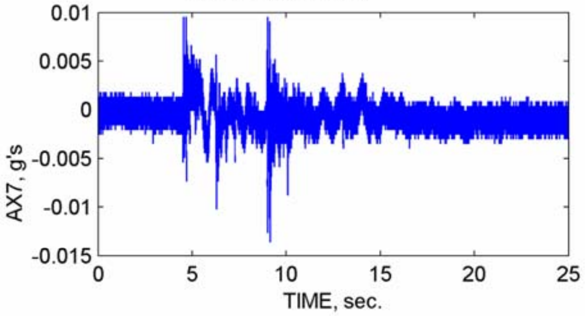

BIE33 Channel 28
F9, kips
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.


BIE33 Channel 29
F10, kips
60
40
20
0
-20
0
5
10
15
20
25
TIME, sec.

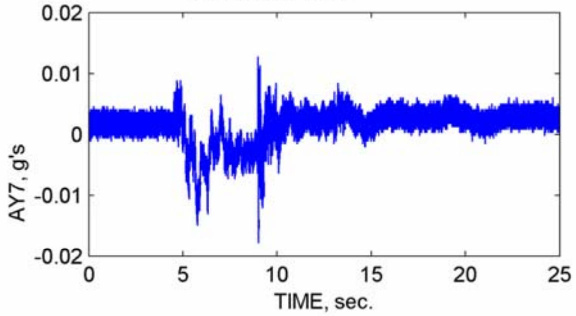

BIE33 Channel 30
F11, kips
100
50
0
-50
TIME, sec.
BIE33 Channel 31
AX1, g's
0
-0.2
-0.4
-0.6
-0.8
-1
TIME, sec.
BIE33 Channel 32
AY1, g's
1.5
1
0.5
0
-0.5
TIME, sec.
BIE33 Channel 33
AZ1, g's
3
2
1
0
-1
-2
TIME, sec.
BIE33 Channel 34
AX2, g's
3
2
1
0
-1
-2
TIME, sec.
BIE33 Channel 35
AY2, g's
3
2
1
0
-1
-2
TIME, sec.
BIE33 Channel 36
AZ2, g's
3
2
1
0
-1
TIME, sec.
BIE33 Channel 37
AX3, g's
1.5
1
0.5
0
TIME, sec.
0
5
10
15
20
25


BIE33 Channel 38
AY3, g's
1
0.5
0
-0.5
TIME, sec.
0
5
10
15
20
25
BIE33 Channel 39
AZ3, g's
1.5
1
0.5
0
-0.5
-1
TIME, sec.
BIE33 Channel 40
AX4, g's
0.05
0
-0.05
-0.1
-0.15
TIME, sec.
BIE33 Channel 41
AY4, g's
0.3
0.2
0.1
0
-0.1
TIME, sec.
BIE33 Channel 42
AX5, g's
0.3
0.2
0.1
0
-0.1
-0.2
TIME, sec.
BIE33 Channel 43
AY5, g's
0.4
0.2
0
-0.2
-0.4
TIME, sec.
BIE33 Channel 44
AX6, g's
0.05
0
-0.05
TIME, sec.
BIE33 Channel 45
AY6, g's
0.1
0.05
0
-0.05
-0.1
TIME, sec.

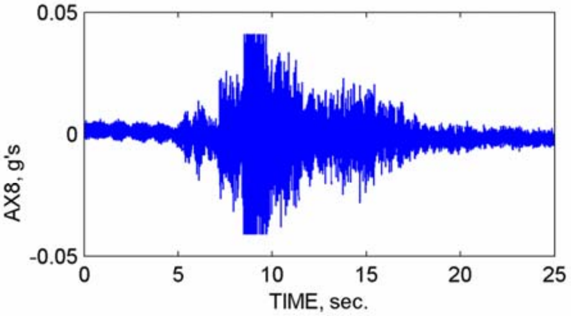
BIE33 Channel 46



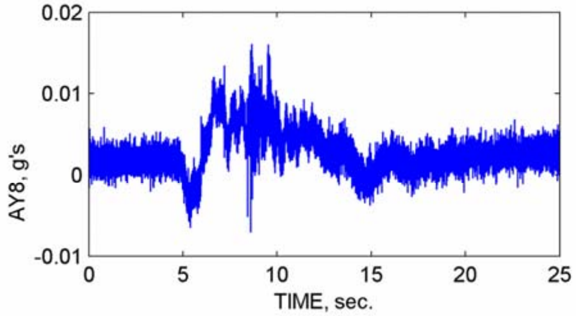
BIE33 Channel 47



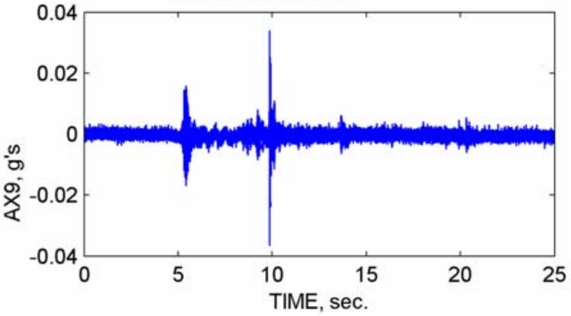
BIE33 Channel 48



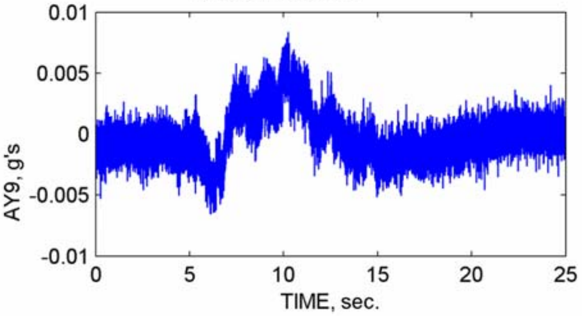
BIE33 Channel 49



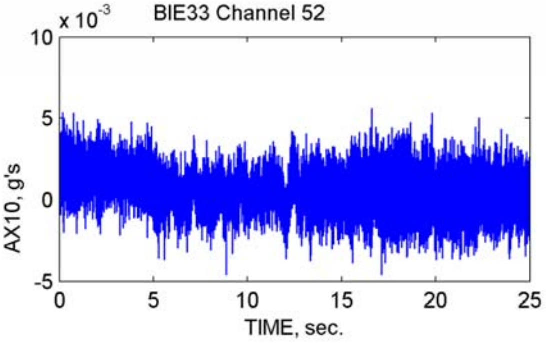
BIE33 Channel 50



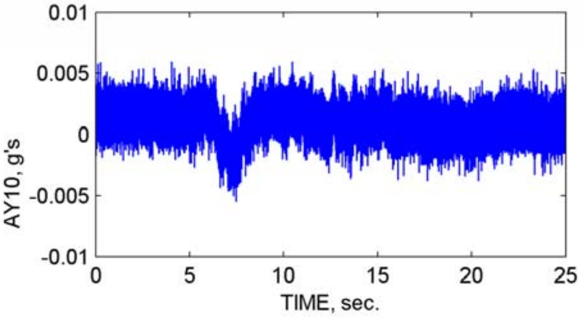
BIE33 Channel 51

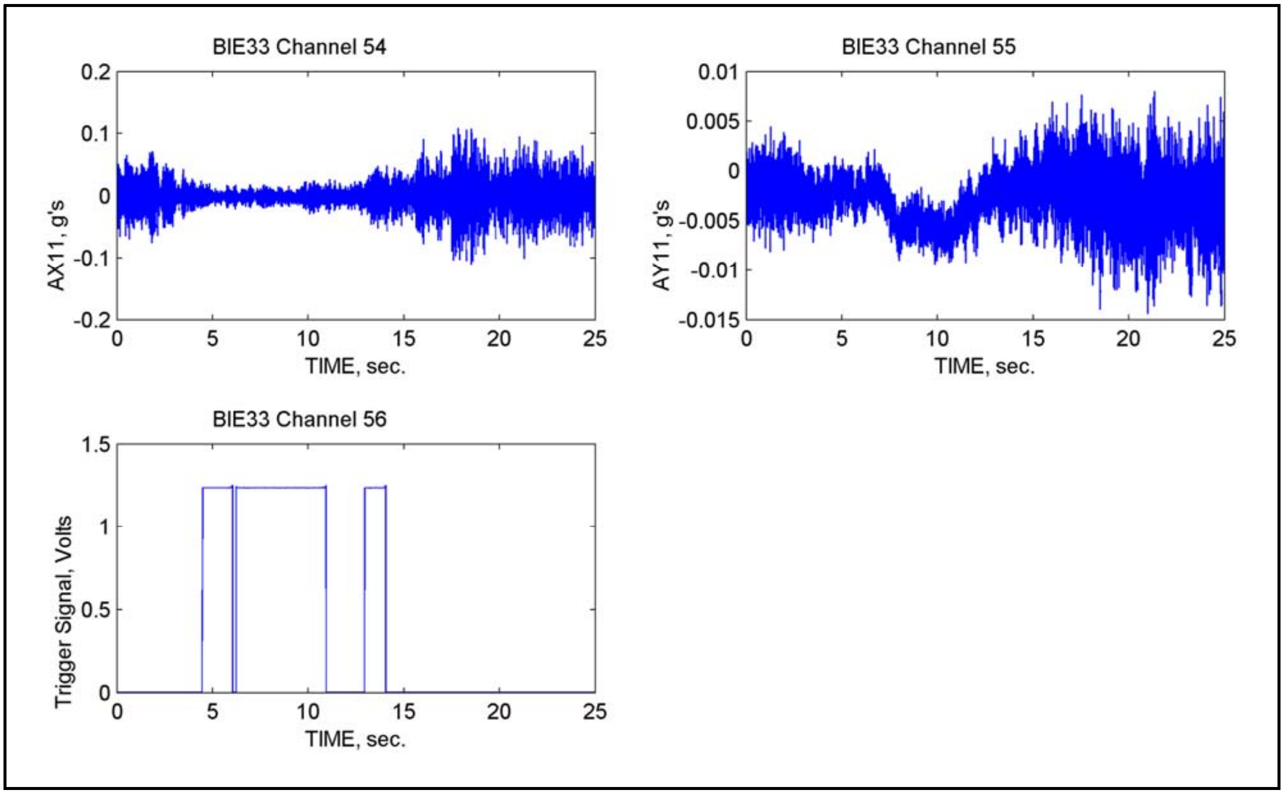


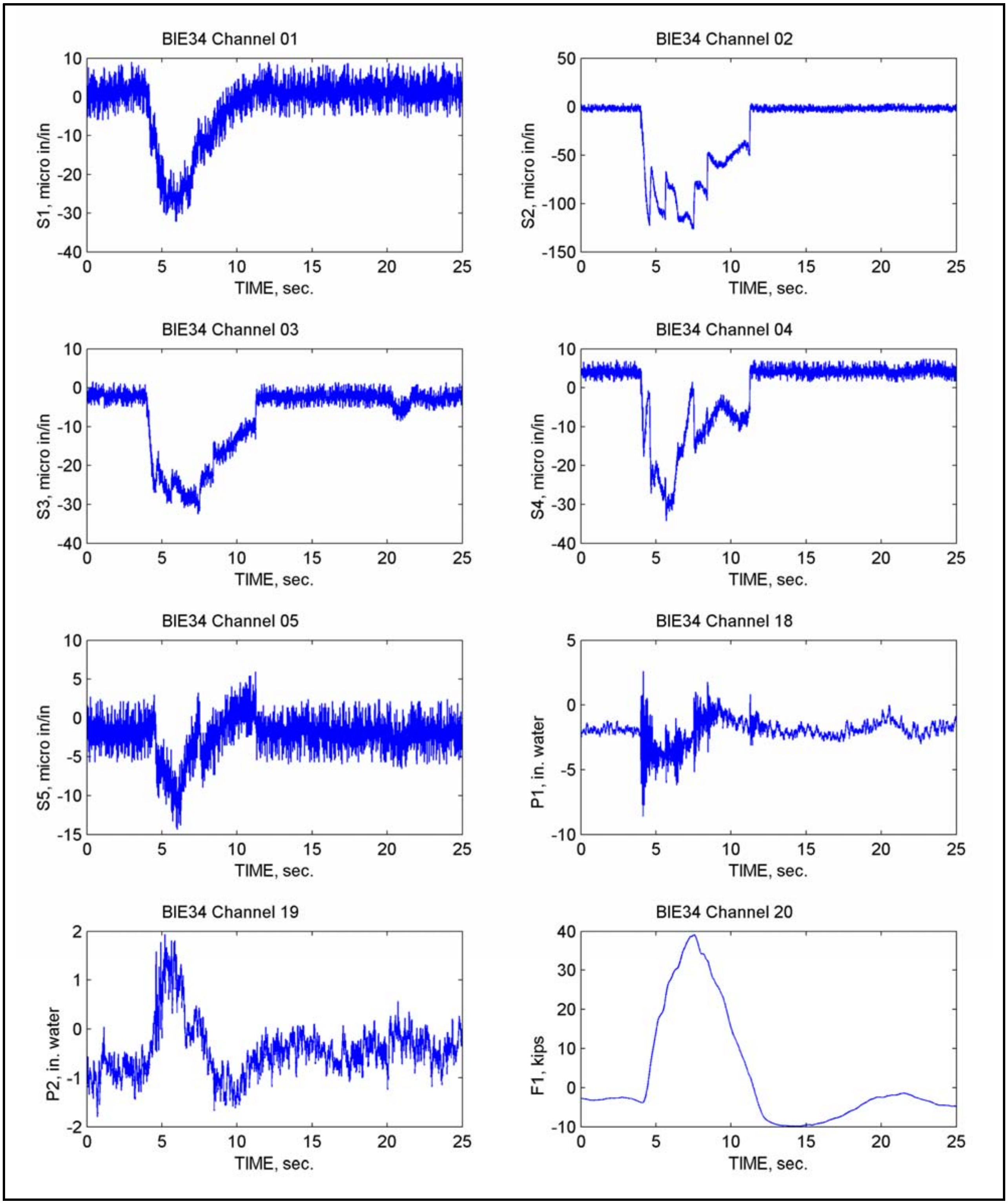
BIE33 Channel 52

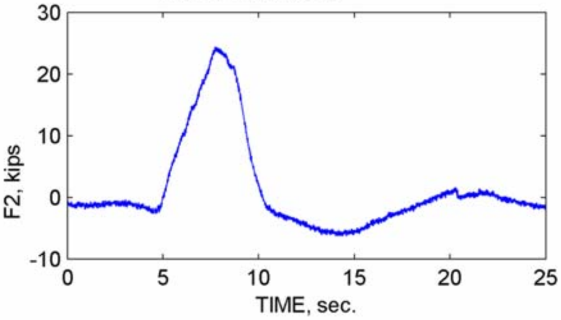


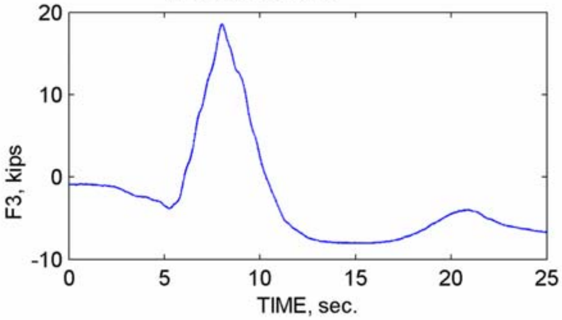
BIE33 Channel 53

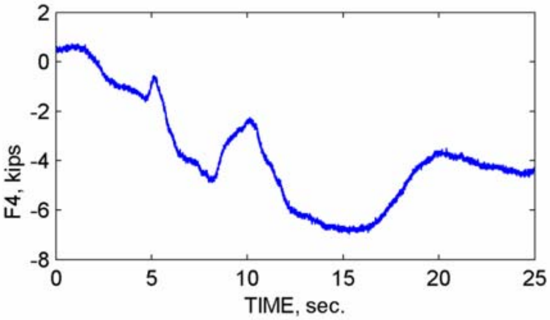


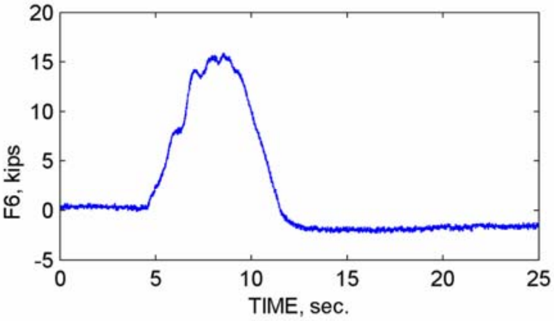

BIE33 Channel 54
AX11, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.
BIE33 Channel 55
AY11, g's
0.01
0.005
0
-0.005
-0.01
-0.015
0
5
10
15
20
25
TIME, sec.
BIE33 Channel 56
Trigger Signal, Volts
1.5
1
0.5
0
0
5
10
15
20
25
TIME, sec.

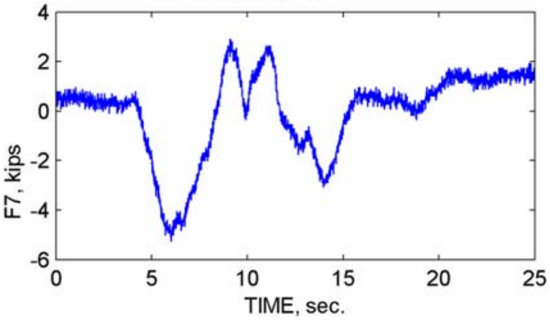

BIE34 Channel 01
S1, micro in/in
10
0
-10
-20
-30
-40
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 02
S2, micro in/in
50
0
-50
-100
-150
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 03
S3, micro in/in
10
0
-10
-20
-30
-40
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 04
S4, micro in/in
10
0
-10
-20
-30
-40
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 05
S5, micro in/in
10
5
0
-5
-10
-15
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 18
P1, in. water
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 19
P2, in. water
2
1
0
-1
-2
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 20
F1, kips
40
30
20
10
0
-10
0
5
10
15
20
25
TIME, sec.

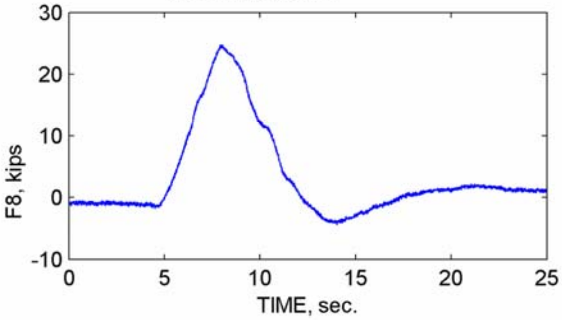

BIE34 Channel 21

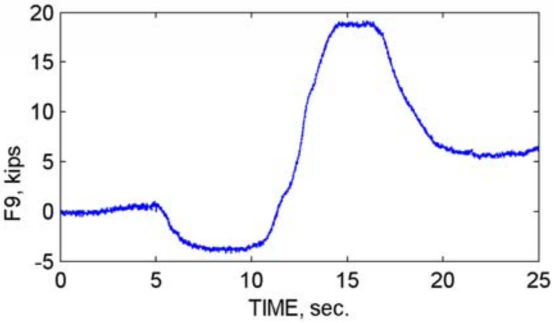

BIE34 Channel 22

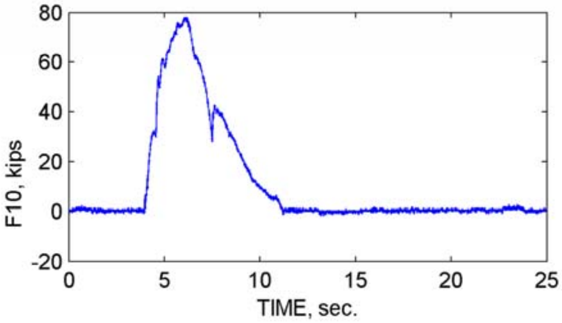

BIE34 Channel 23

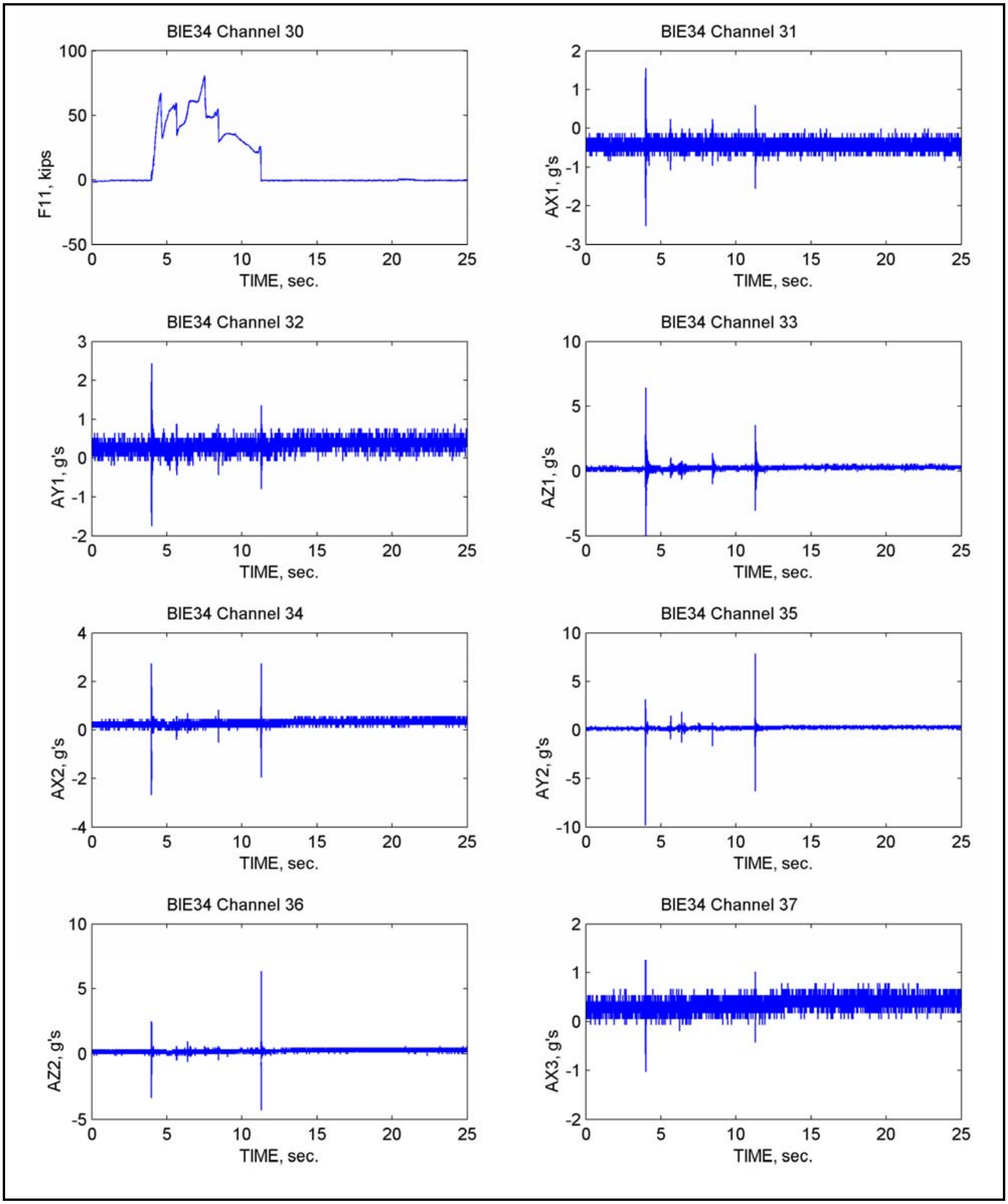

BIE34 Channel 25

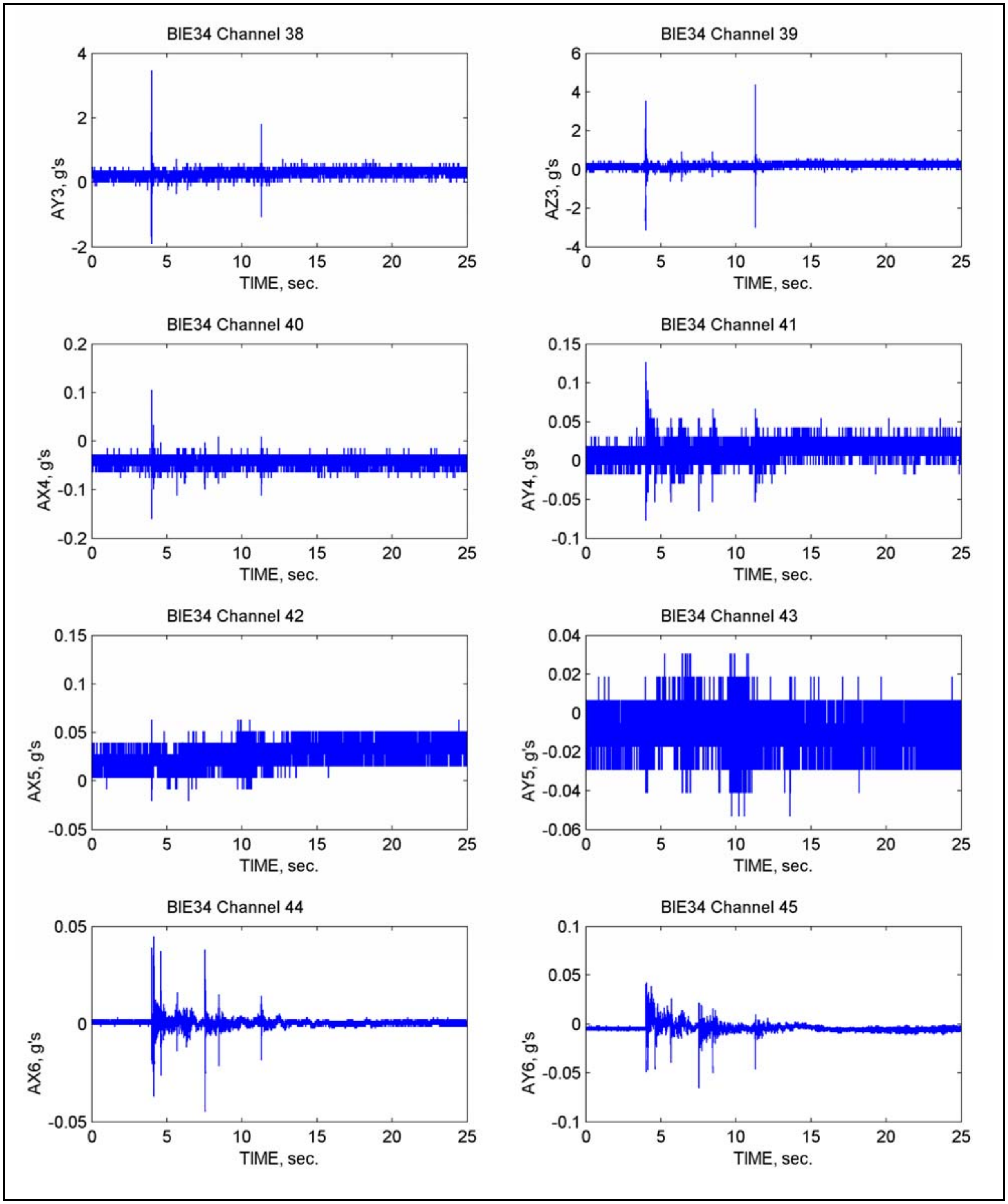

BIE34 Channel 26

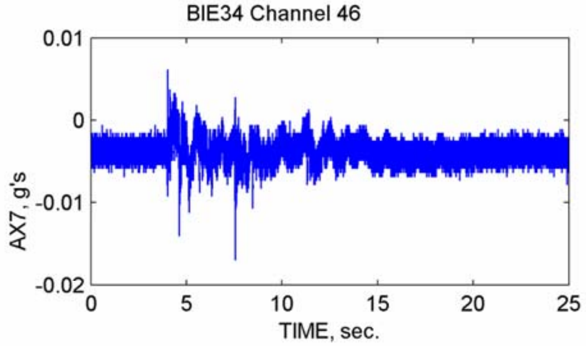

BIE34 Channel 27

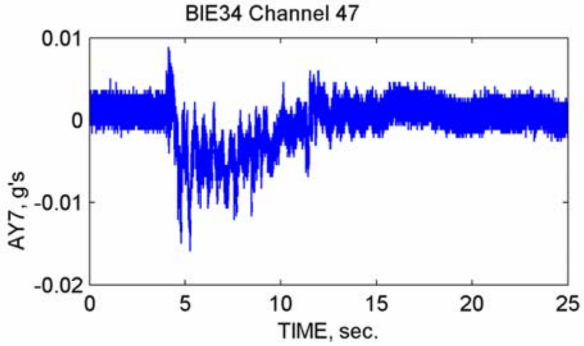

BIE34 Channel 28

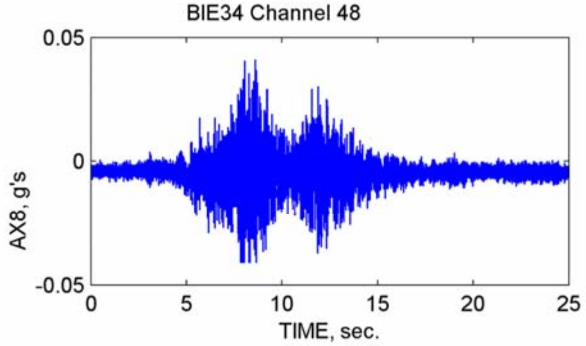

BIE34 Channel 29

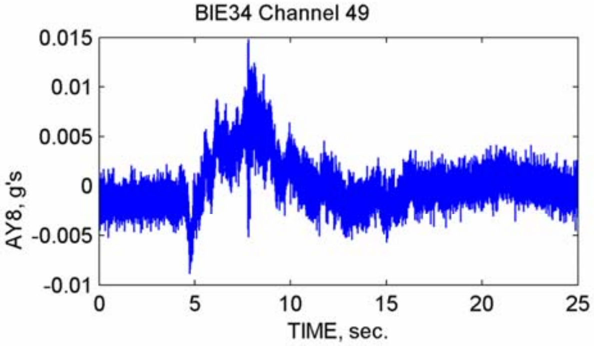

BIE34 Channel 30
F11, kips
100
50
0
-50
TIME, sec.
0
5
10
15
20
25
BIE34 Channel 31
AX1, g's
2
1
0
-1
-2
-3
TIME, sec.
BIE34 Channel 32
AY1, g's
3
2
1
0
-1
-2
TIME, sec.
BIE34 Channel 33
AZ1, g's
10
5
0
-5
TIME, sec.
BIE34 Channel 34
AX2, g's
4
2
0
-2
-4
TIME, sec.
BIE34 Channel 35
AY2, g's
10
5
0
-5
-10
TIME, sec.
BIE34 Channel 36
AZ2, g's
10
5
0
-5
TIME, sec.
BIE34 Channel 37
AX3, g's
2
1
0
-1
-2
TIME, sec.

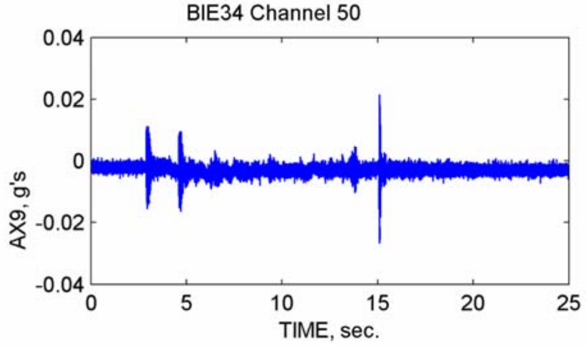

BIE34 Channel 38
AY3, g's
4
2
0
-2
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 39
AZ3, g's
6
4
2
0
-2
-4
TIME, sec.
BIE34 Channel 40
AX4, g's
0.2
0.1
0
-0.1
-0.2
TIME, sec.
BIE34 Channel 41
AY4, g's
0.15
0.1
0.05
0
-0.05
-0.1
TIME, sec.
BIE34 Channel 42
AX5, g's
0.15
0.1
0.05
0
-0.05
TIME, sec.
BIE34 Channel 43
AY5, g's
0.04
0.02
0
-0.02
-0.04
-0.06
TIME, sec.
BIE34 Channel 44
AX6, g's
0.05
0
-0.05
TIME, sec.
BIE34 Channel 45
AY6, g's
0.1
0.05
0
-0.05
-0.1
TIME, sec.

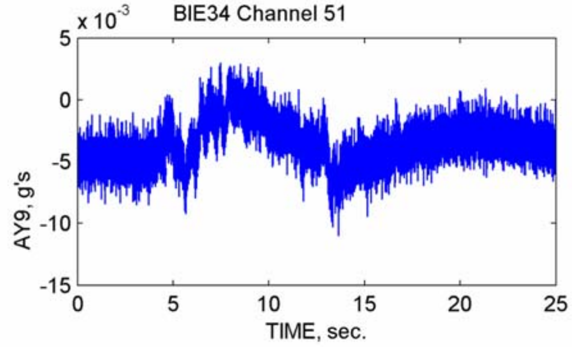

BIE34 Channel 46
0.01
0
-0.01
-0.02
AX7, g's
0
5
10
15
20
25
TIME, sec.

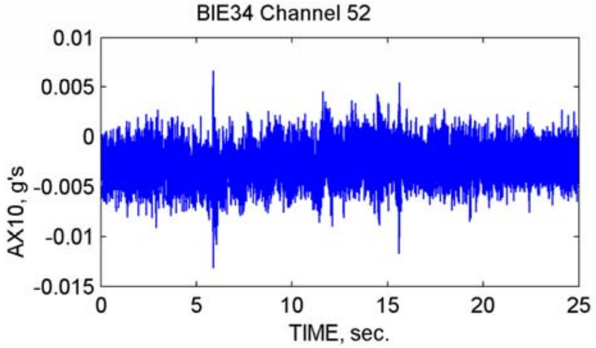

BIE34 Channel 47
0.01
0
-0.01
-0.02
AY7, g's
0
5
10
15
20
25
TIME, sec.

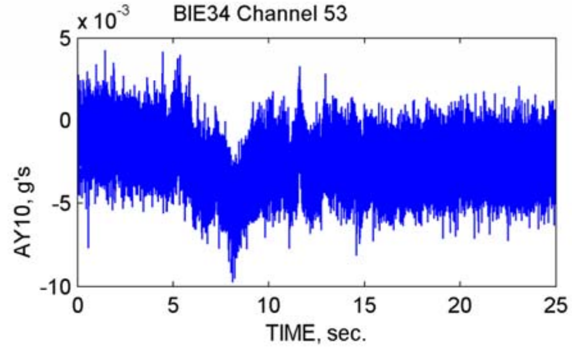

BIE34 Channel 48
0.05
0
-0.05
AX8, g's
0
5
10
15
20
25
TIME, sec.

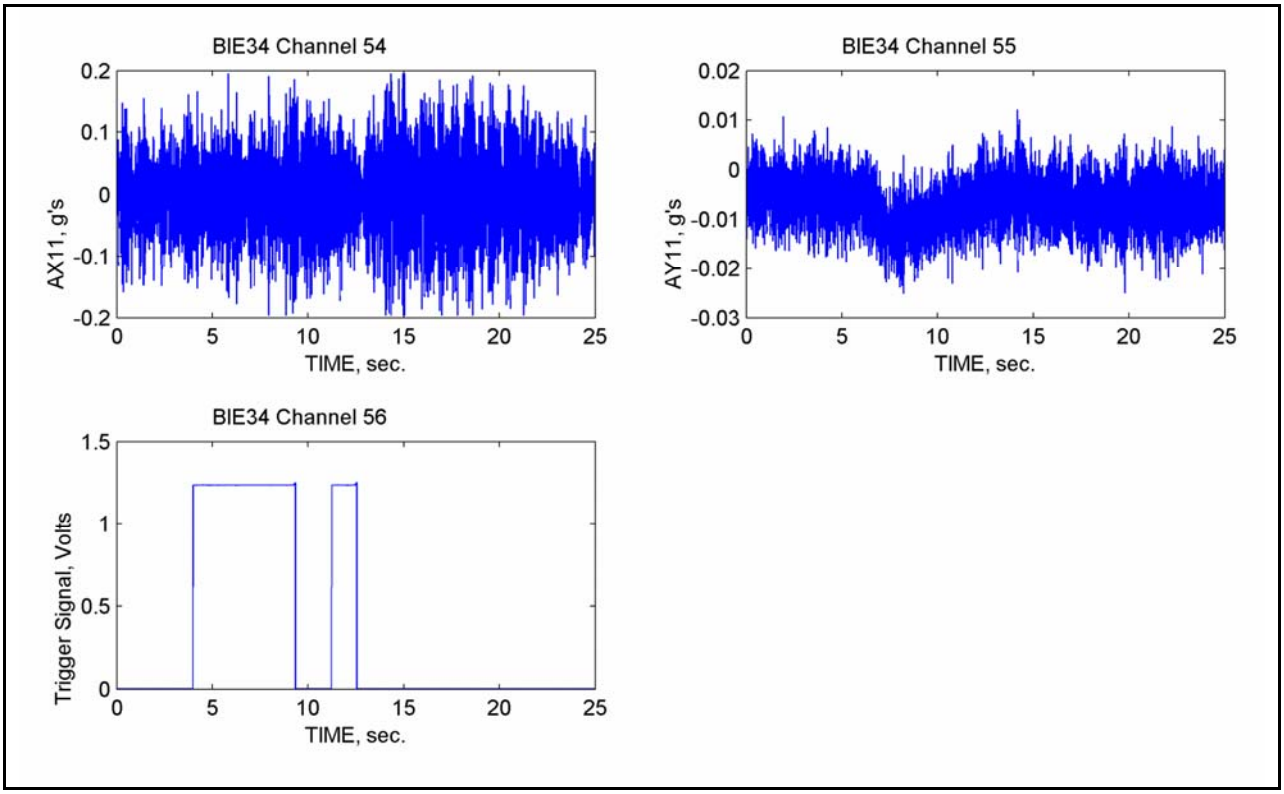

BIE34 Channel 49
0.015
0.01
0.005
0
-0.005
-0.01
AY8, g's
0
5
10
15
20
25
TIME, sec.

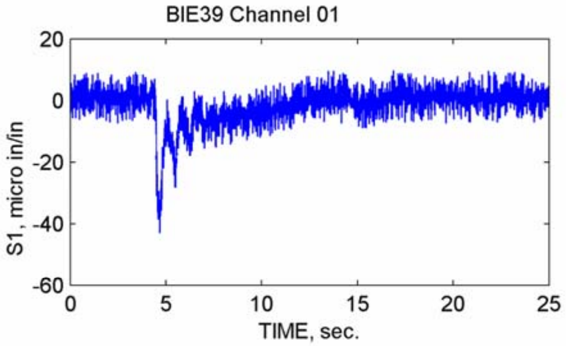

BIE34 Channel 50
0.04
0.02
0
-0.02
-0.04
AX9, g's
0
5
10
15
20
25
TIME, sec.

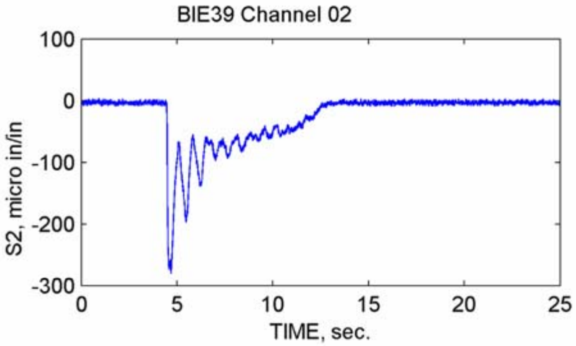

x 10^-3
BIE34 Channel 51
5
0
-5
-10
-15
AY9, g's
0
5
10
15
20
25
TIME, sec.

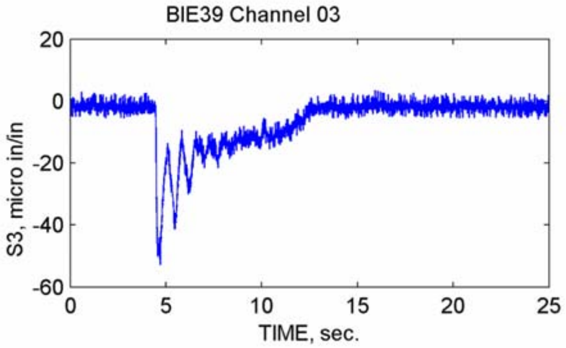

BIE34 Channel 52
0.01
0.005
0
-0.005
-0.01
-0.015
AX10, g's
0
5
10
15
20
25
TIME, sec.

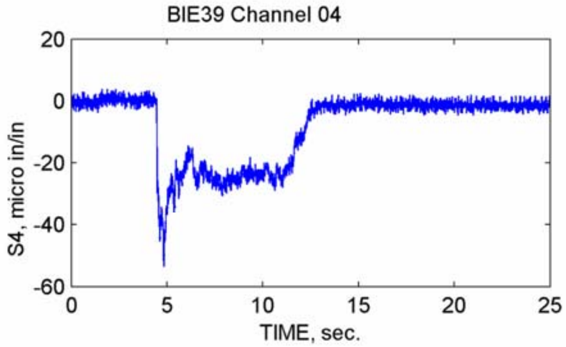

x 10^-3
BIE34 Channel 53
5
0
-5
-10
AY10, g's
0
5
10
15
20
25
TIME, sec.

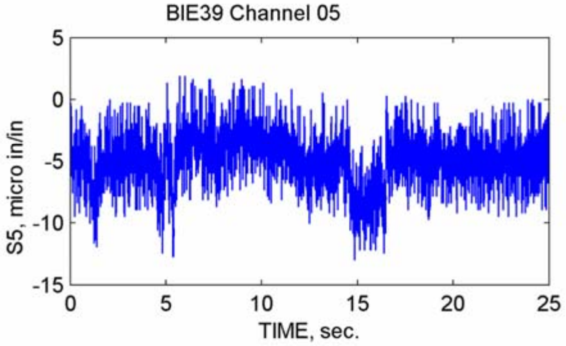

BIE34 Channel 54
AX11, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 55
AY11, g's
0.02
0.01
0
-0.01
-0.02
-0.03
0
5
10
15
20
25
TIME, sec.
BIE34 Channel 56
Trigger Signal, Volts
1.5
1
0.5
0
0
5
10
15
20
25
TIME, sec.

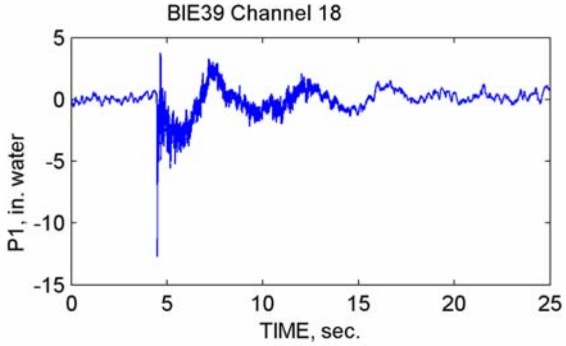

BIE39 Channel 01

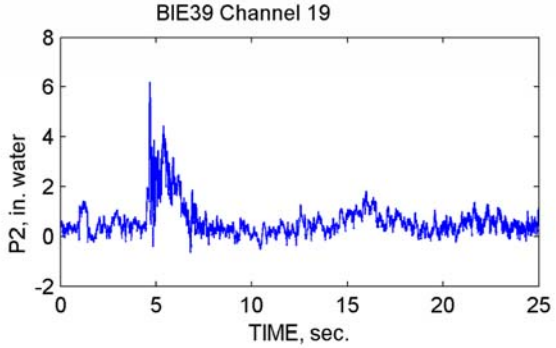

BIE39 Channel 02

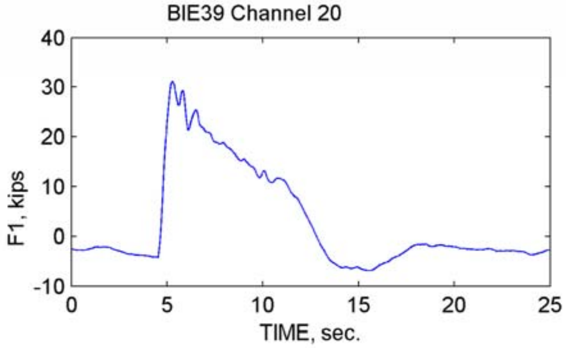

BIE39 Channel 03

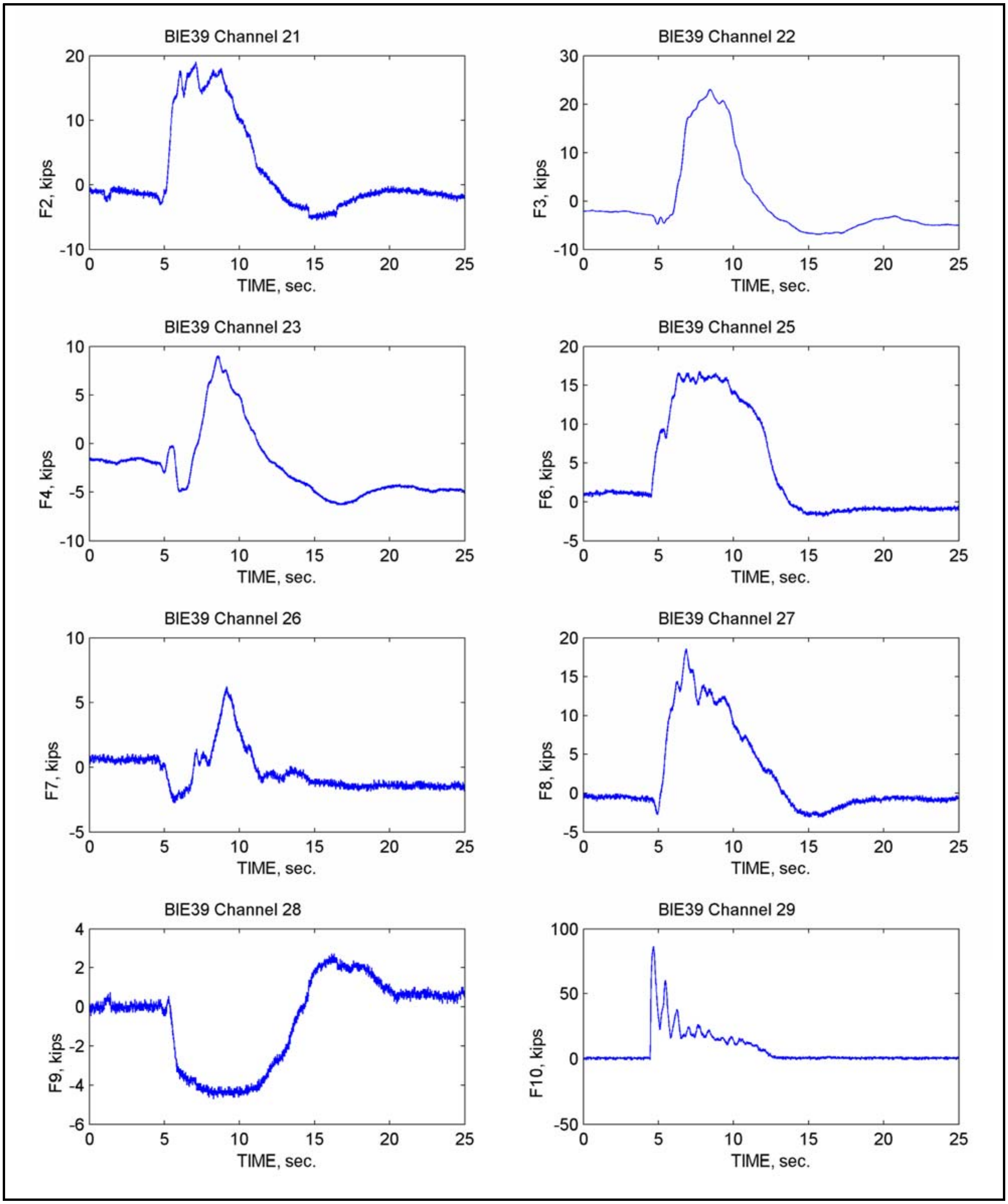

BIE39 Channel 04


BIE39 Channel 05

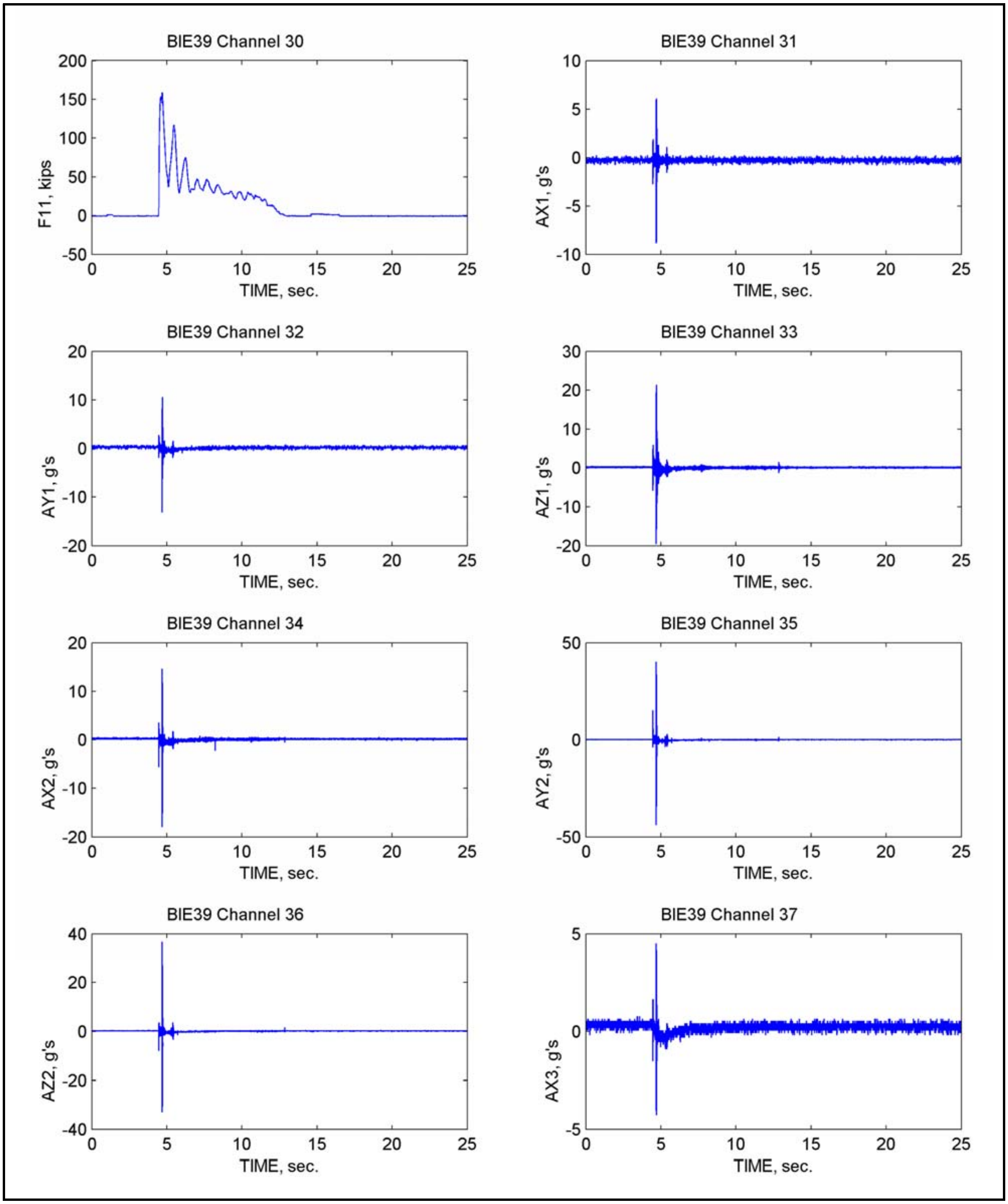

BIE39 Channel 18

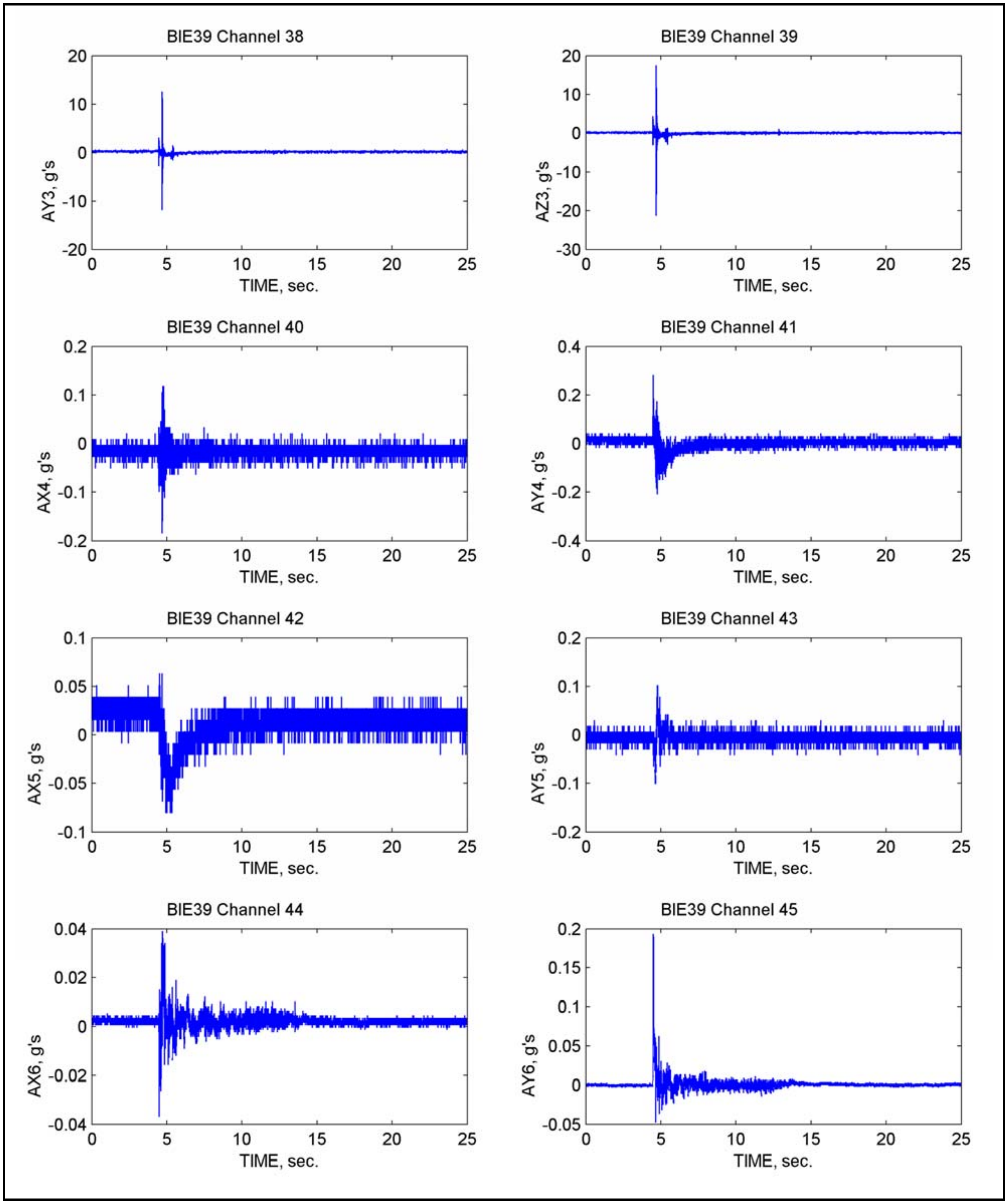

BIE39 Channel 19

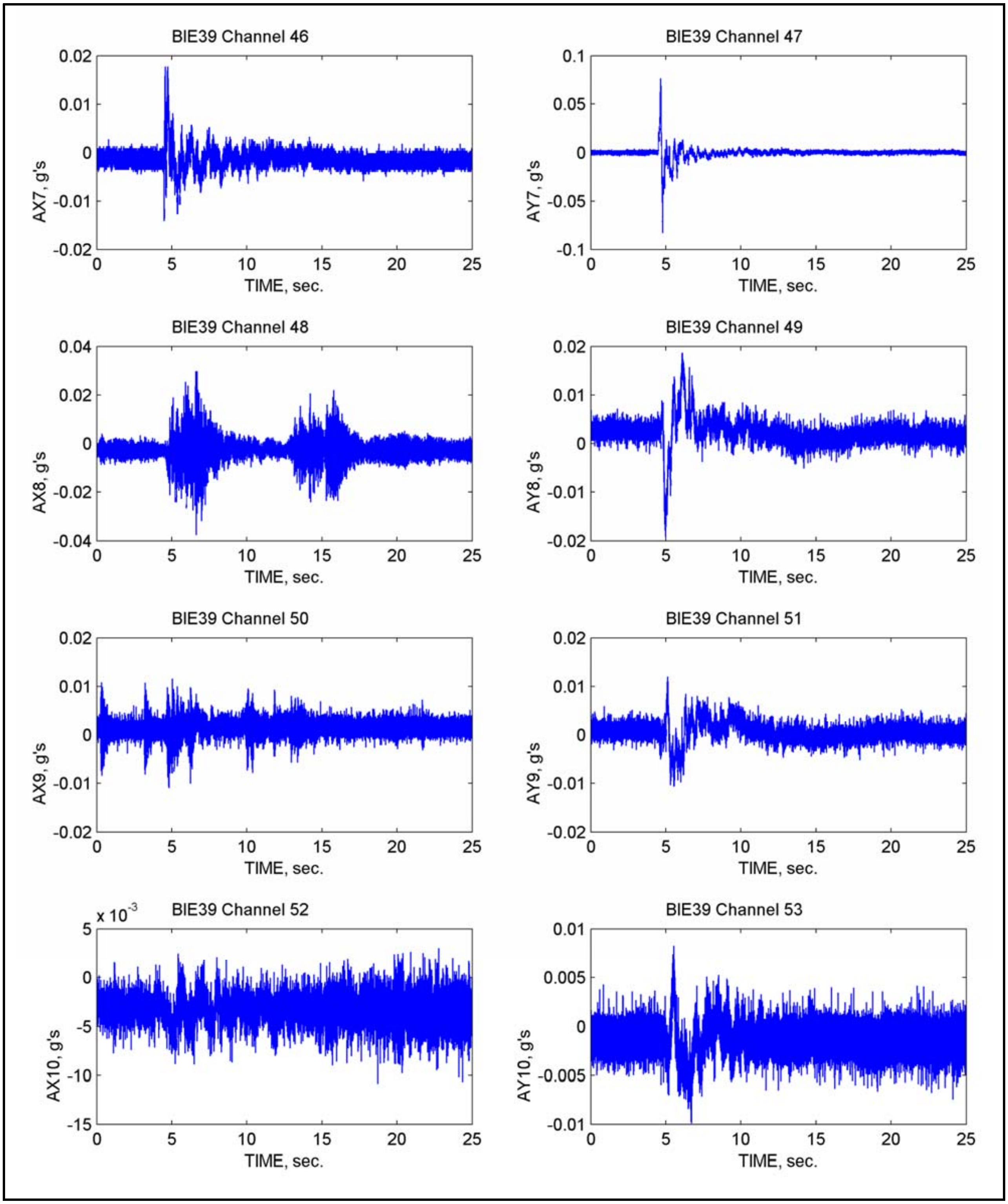

BIE39 Channel 20

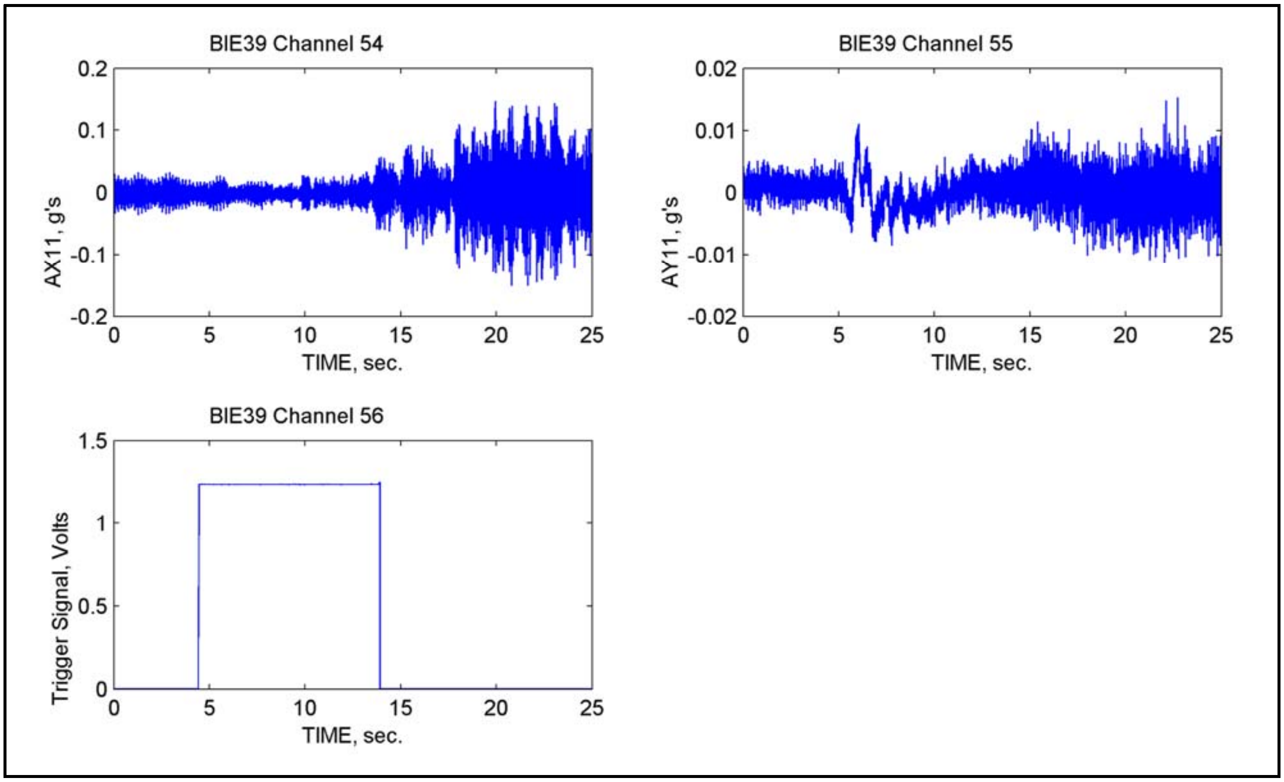


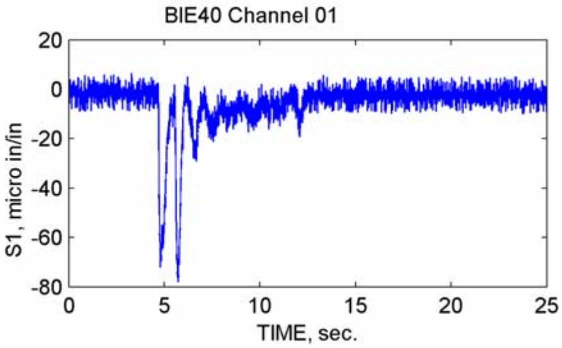
BIE39 Channel 21
F2, kips
20
10
0
-10
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 22
F3, kips
30
20
10
0
-10
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 23
F4, kips
10
5
0
-5
-10
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 25
F6, kips
20
15
10
5
0
-5
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 26
F7, kips
10
5
0
-5
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 27
F8, kips
20
15
10
5
0
-5
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 28
F9, kips
4
2
0
-2
-4
-6
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 29
F10, kips
100
50
0
-50
0
5
10
15
20
25
TIME, sec.

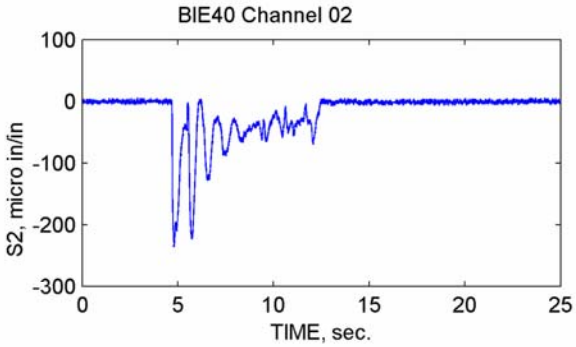

BIE39 Channel 30
F11, kips
200
150
100
50
0
-50
TIME, sec.
0
5
10
15
20
25
BIE39 Channel 31
AX1, g's
10
5
0
-5
-10
TIME, sec.
BIE39 Channel 32
AY1, g's
20
10
0
-10
-20
TIME, sec.
BIE39 Channel 33
AZ1, g's
30
20
10
0
-10
-20
TIME, sec.
BIE39 Channel 34
AX2, g's
20
10
0
-10
-20
TIME, sec.
BIE39 Channel 35
AY2, g's
50
0
-50
TIME, sec.
BIE39 Channel 36
AZ2, g's
40
20
0
-20
-40
TIME, sec.
BIE39 Channel 37
AX3, g's
5
0
-5
TIME, sec.

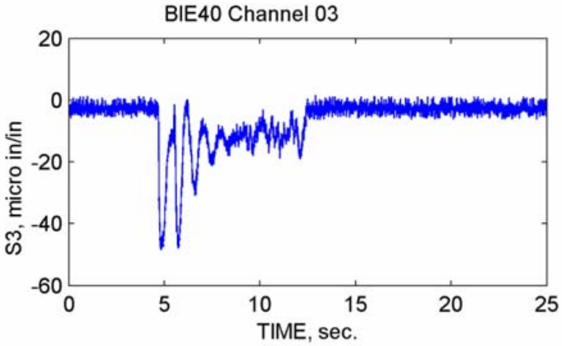

BIE39 Channel 38
AY3, g's
20
10
0
-10
-20
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 39
AZ3, g's
20
10
0
-10
-20
-30
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 40
AX4, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 41
AY4, g's
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 42
AX5, g's
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 43
AY5, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 44
AX6, g's
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 45
AY6, g's
0.2
0.15
0.1
0.05
0
-0.05
0
5
10
15
20
25
TIME, sec.

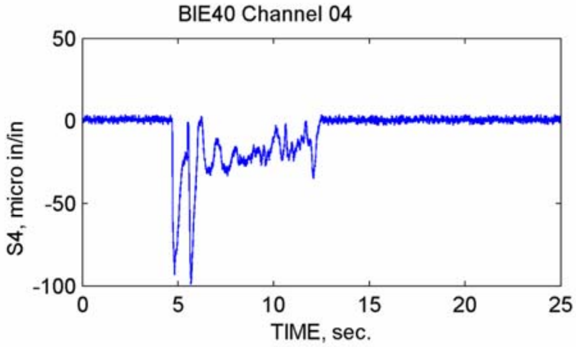

BIE39 Channel 46
AX7, g's
0.02
0.01
0
-0.01
-0.02
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 47
AY7, g's
0.1
0.05
0
-0.05
-0.1
TIME, sec.
BIE39 Channel 48
AX8, g's
0.04
0.02
0
-0.02
-0.04
TIME, sec.
BIE39 Channel 49
AY8, g's
0.02
0.01
0
-0.01
-0.02
TIME, sec.
BIE39 Channel 50
AX9, g's
0.02
0.01
0
-0.01
-0.02
TIME, sec.
BIE39 Channel 51
AY9, g's
0.02
0.01
0
-0.01
-0.02
TIME, sec.
x 10^-3
BIE39 Channel 52
AX10, g's
5
0
-5
-10
-15
TIME, sec.
BIE39 Channel 53
AY10, g's
0.01
0.005
0
-0.005
-0.01
TIME, sec.

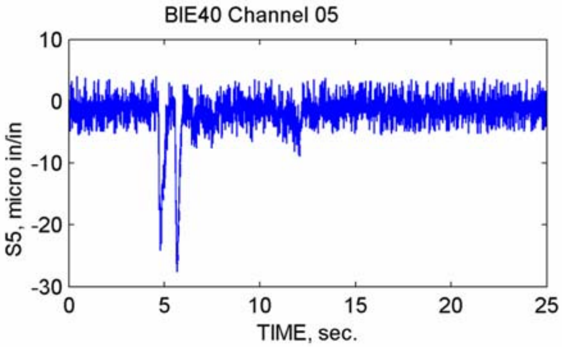

BIE39 Channel 54
AX11, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 55
AY11, g's
0.02
0.01
0
-0.01
-0.02
0
5
10
15
20
25
TIME, sec.
BIE39 Channel 56
Trigger Signal, Volts
1.5
1
0.5
0
0
5
10
15
20
25
TIME, sec.

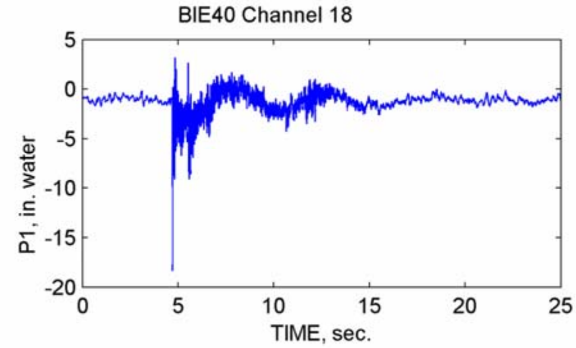

BIE40 Channel 01
S1, micro in/in
20
0
-20
-40
-60
-80
0
5
10
15
20
25
TIME, sec.

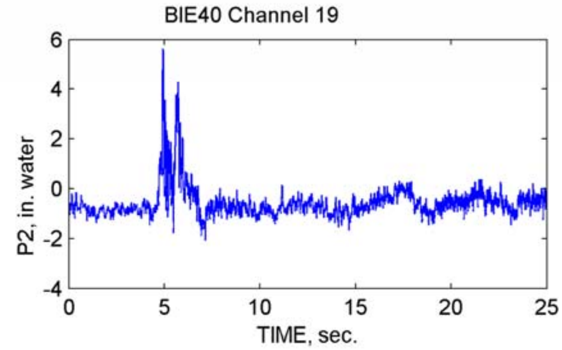

BIE40 Channel 02
S2, micro in/in
100
0
-100
-200
-300
0
5
10
15
20
25
TIME, sec.

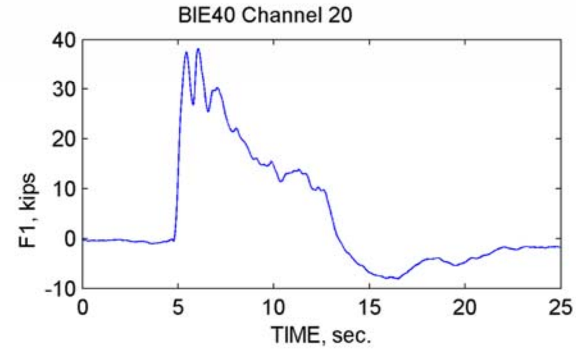

BIE40 Channel 03
S3, micro in/in
20
0
-20
-40
-60
0
5
10
15
20
25
TIME, sec.

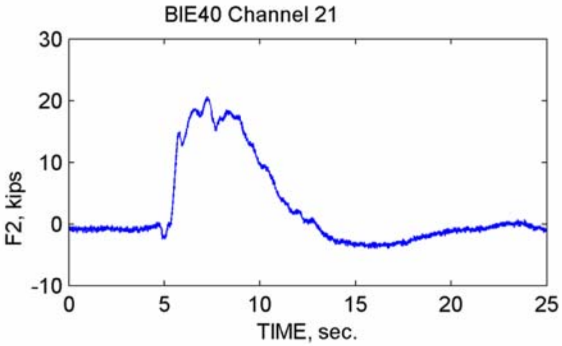

BIE40 Channel 04
S4, micro in/in
50
0
-50
-100
0
5
10
15
20
25
TIME, sec.

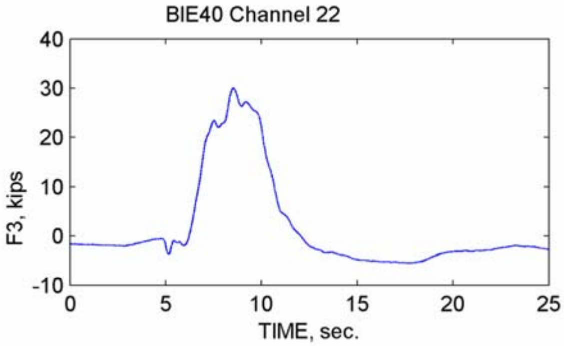

BIE40 Channel 05
S5, micro in/in
10
0
-10
-20
-30
0
5
10
15
20
25
TIME, sec.

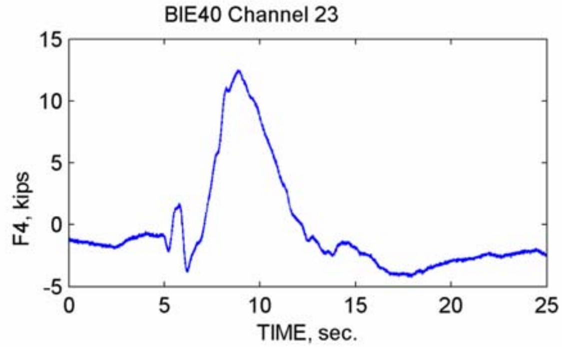

BIE40 Channel 18
P1, in. water
5
0
-5
-10
-15
-20
0
5
10
15
20
25
TIME, sec.

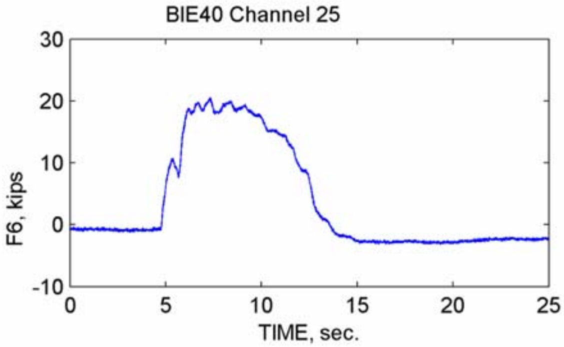

BIE40 Channel 19
P2, in. water
6
4
2
0
-2
-4
0
5
10
15
20
25
TIME, sec.

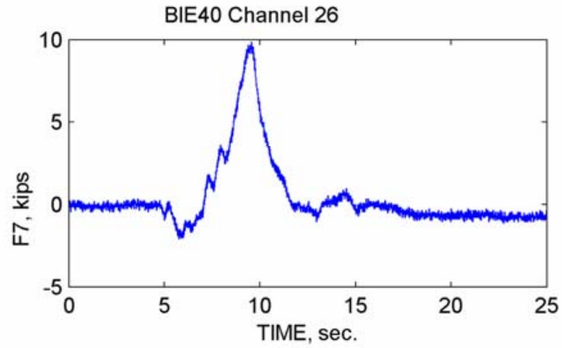

BIE40 Channel 20
F1, kips
40
30
20
10
0
-10
0
5
10
15
20
25
TIME, sec.

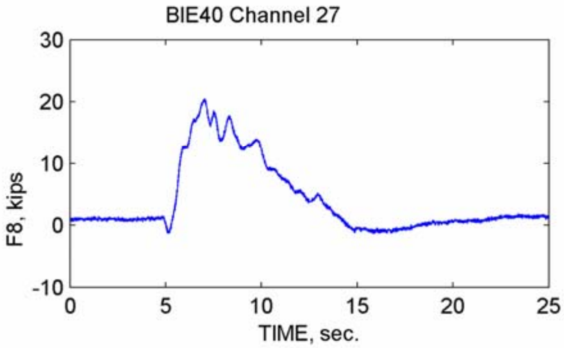

BIE40 Channel 21
F2, kips
30
20
10
0
-10
0
5
10
15
20
25
TIME, sec.

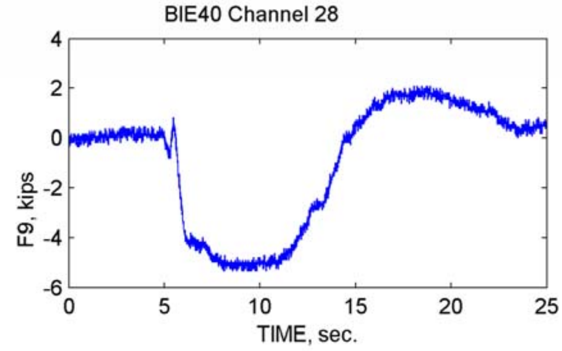

BIE40 Channel 22
F3, kips
40
30
20
10
0
-10
0
5
10
15
20
25
TIME, sec.

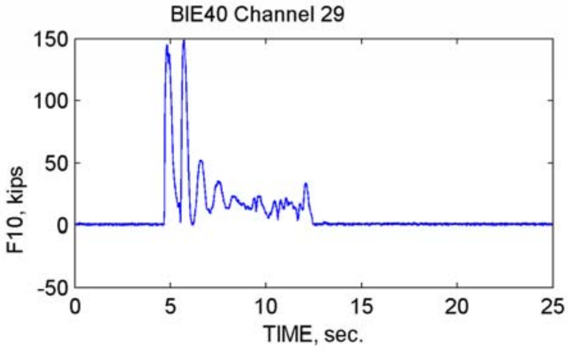

BIE40 Channel 23
F4, kips
15
10
5
0
-5
0
5
10
15
20
25
TIME, sec.


BIE40 Channel 25
F6, kips
30
20
10
0
-10
0
5
10
15
20
25
TIME, sec.

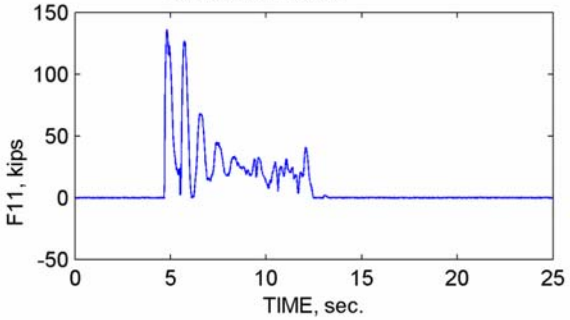

BIE40 Channel 26
F7, kips
10
5
0
-5
0
5
10
15
20
25
TIME, sec.


BIE40 Channel 27
F8, kips
30
20
10
0
-10
0
5
10
15
20
25
TIME, sec.

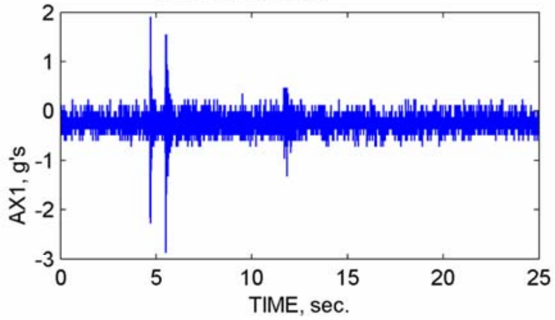

BIE40 Channel 28
F9, kips
4
2
0
-2
-4
-6
0
5
10
15
20
25
TIME, sec.


BIE40 Channel 29
F10, kips
150
100
50
0
-50
0
5
10
15
20
25
TIME, sec.

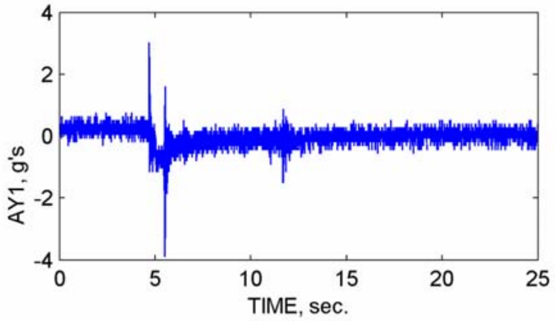
BIE40 Channel 30



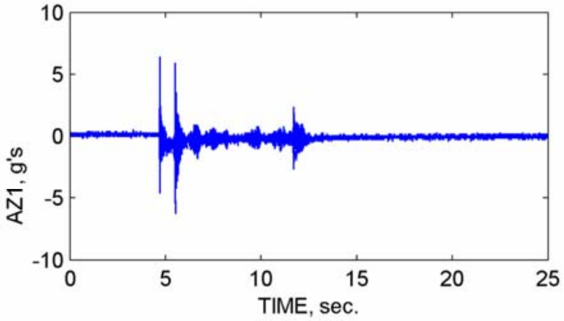
BIE40 Channel 31



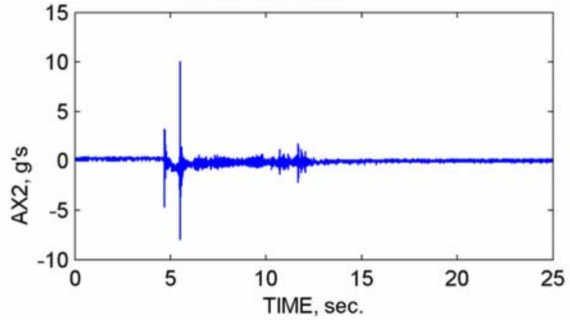
BIE40 Channel 32



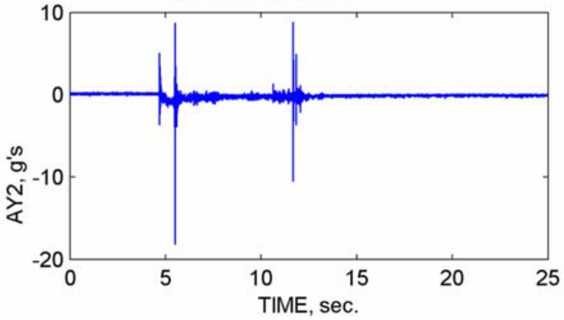
BIE40 Channel 33



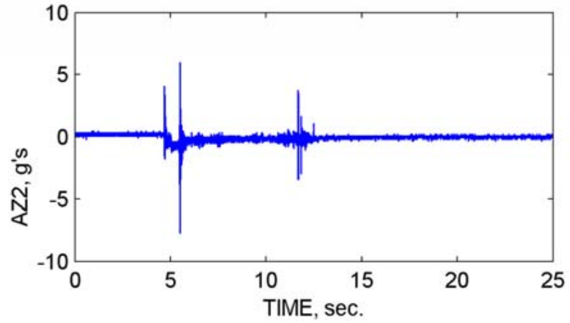
BIE40 Channel 34



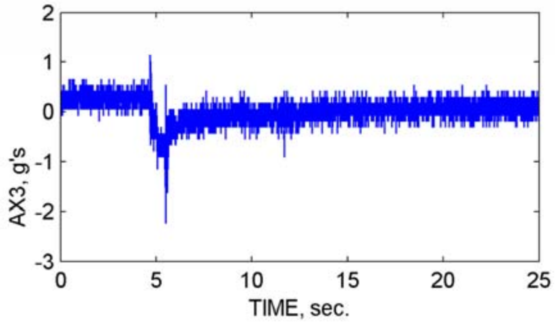
BIE40 Channel 35



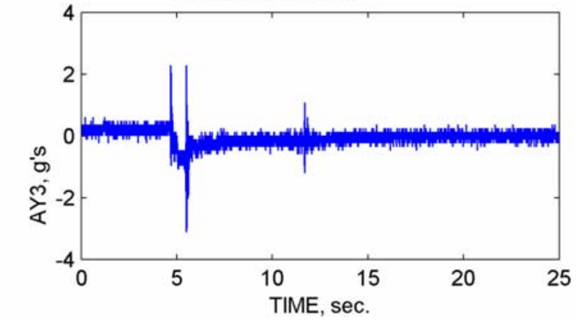
BIE40 Channel 36



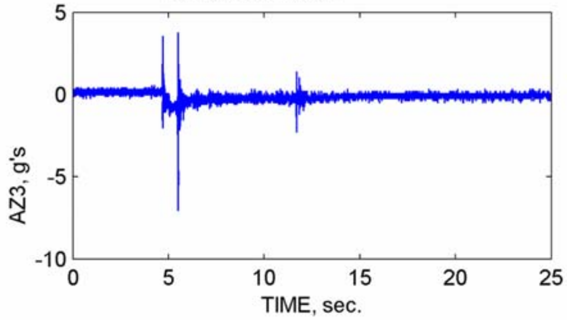
BIE40 Channel 37



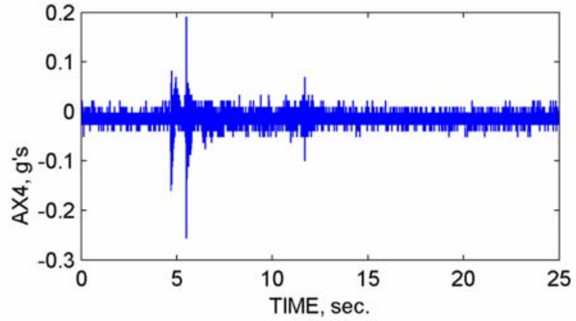
BIE40 Channel 38



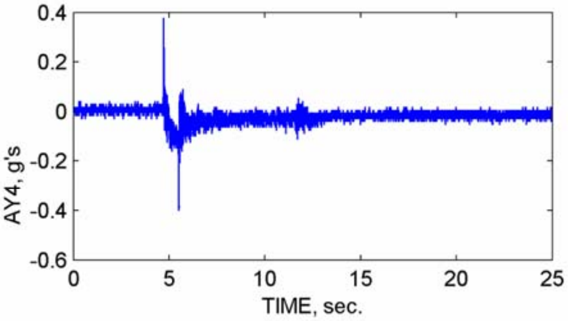
BIE40 Channel 39



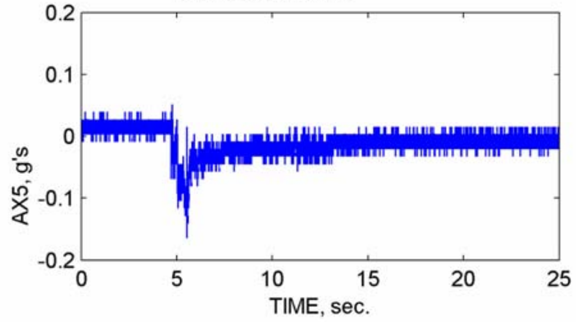
BIE40 Channel 40



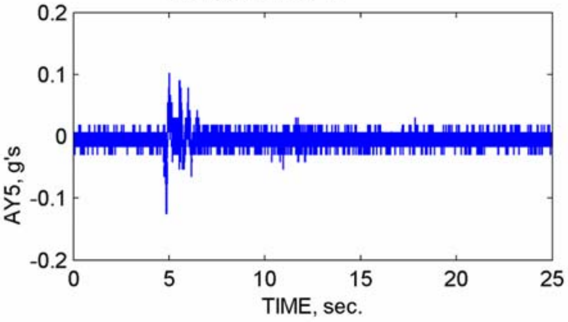
BIE40 Channel 41



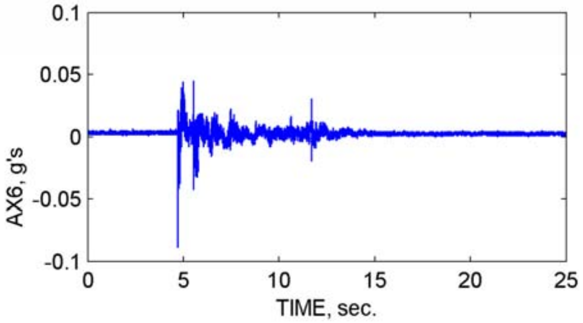
BIE40 Channel 42



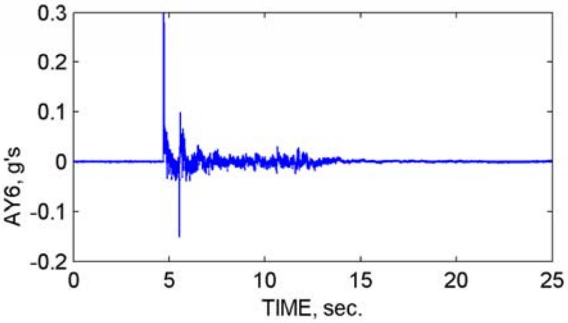
BIE40 Channel 43

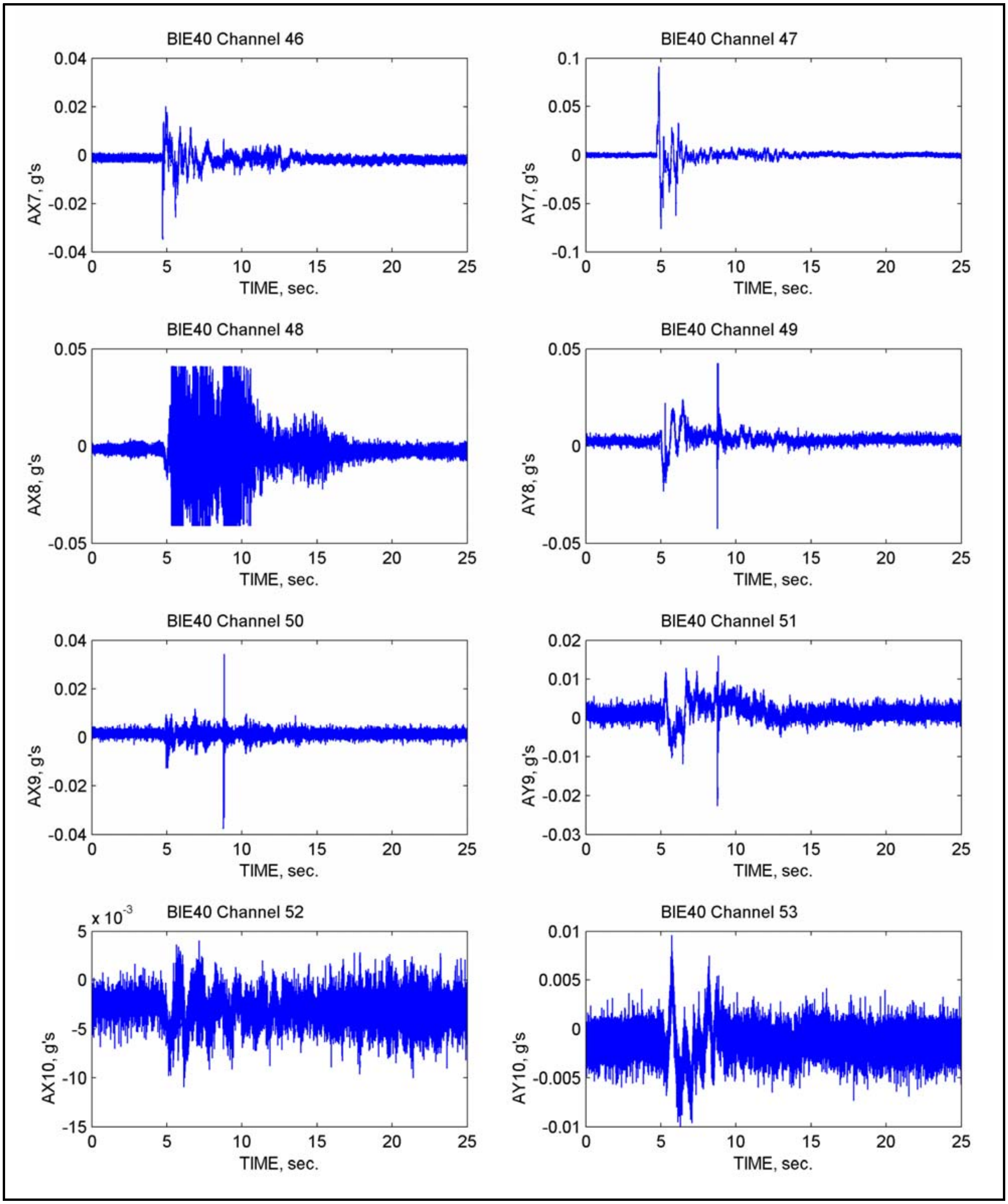


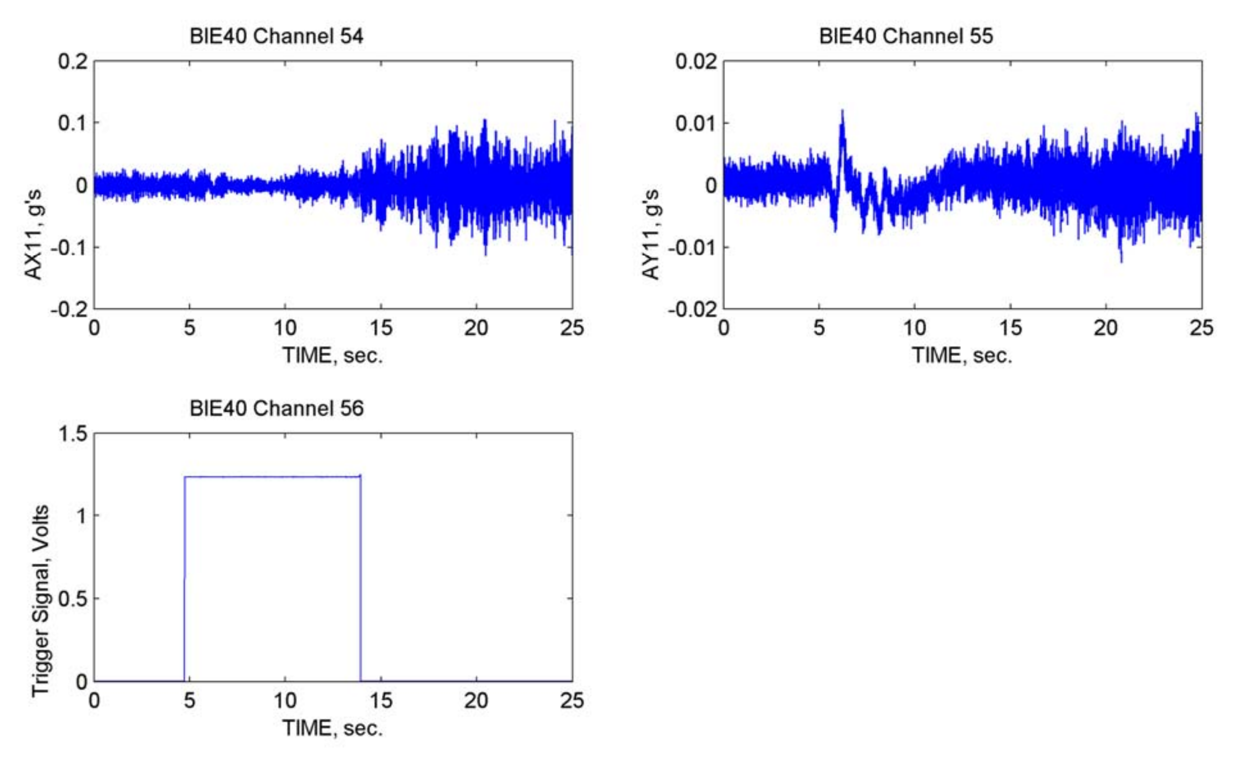
BIE40 Channel 44

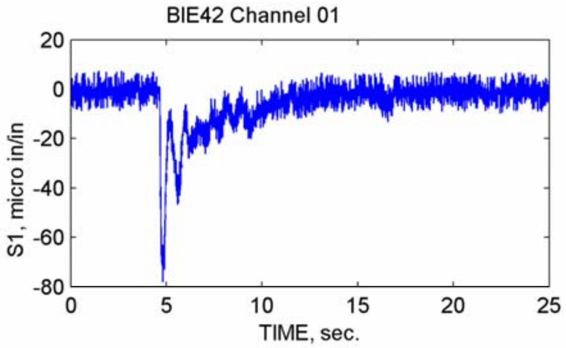


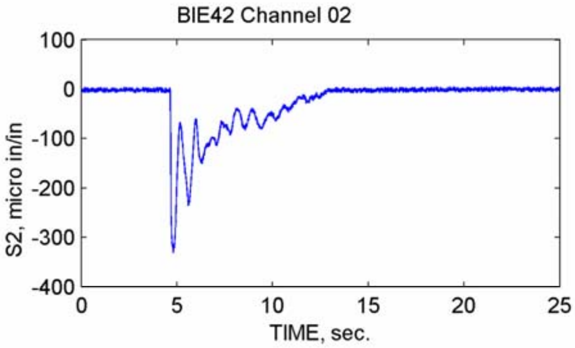
BIE40 Channel 45

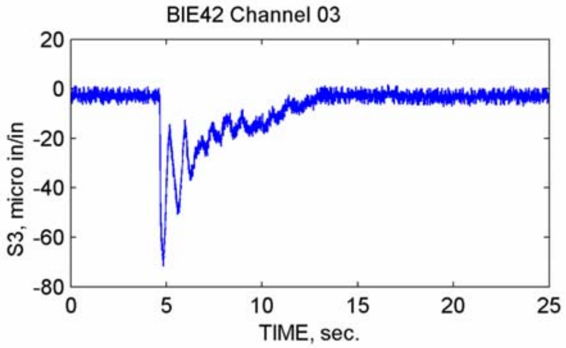


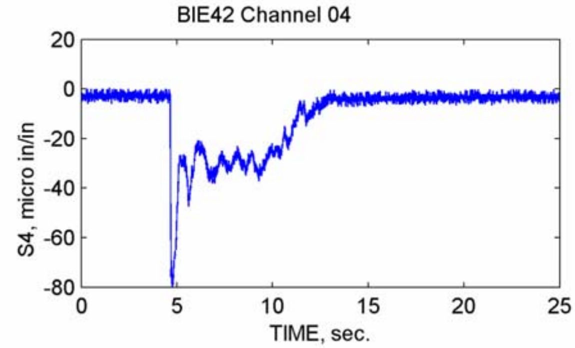

BIE40 Channel 46
AX7, g's
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20
25
TIME, sec.
BIE40 Channel 47
AY7, g's
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
TIME, sec.
BIE40 Channel 48
AX8, g's
0.05
0
-0.05
0
5
10
15
20
25
TIME, sec.
BIE40 Channel 49
AY8, g's
0.05
0
-0.05
0
5
10
15
20
25
TIME, sec.
BIE40 Channel 50
AX9, g's
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20
25
TIME, sec.
BIE40 Channel 51
AY9, g's
0.02
0.01
0
-0.01
-0.02
-0.03
0
5
10
15
20
25
TIME, sec.
x 10-3
BIE40 Channel 52
AX10, g's
5
0
-5
-10
-15
0
5
10
15
20
25
TIME, sec.
BIE40 Channel 53
AY10, g's
0.01
0.005
0
-0.005
-0.01
0
5
10
15
20
25
TIME, sec.

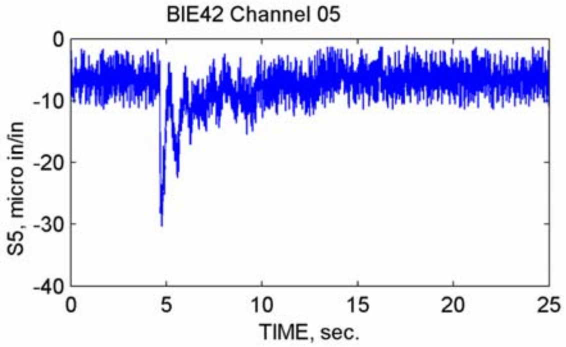

BIE40 Channel 54
AX11, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.
BIE40 Channel 55
AY11, g's
0.02
0.01
0
-0.01
-0.02
0
5
10
15
20
25
TIME, sec.
BIE40 Channel 56
Trigger Signal, Volts
1.5
1
0.5
0
0
5
10
15
20
25
TIME, sec.

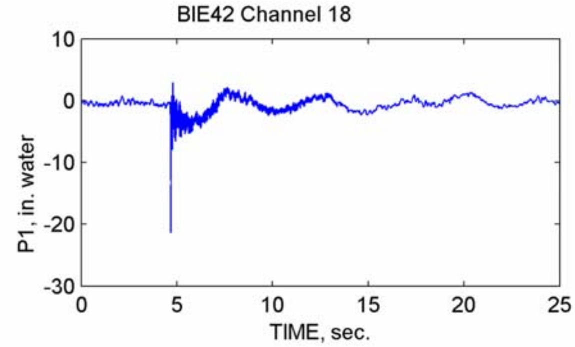

BIE42 Channel 01

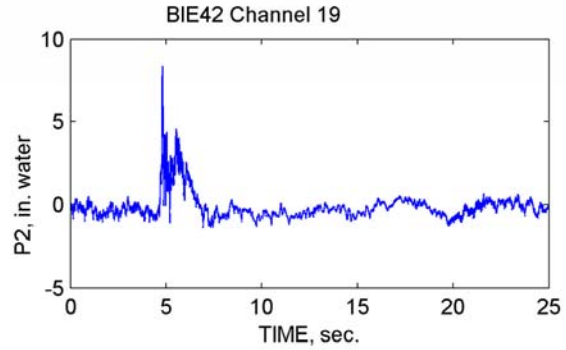

BIE42 Channel 02

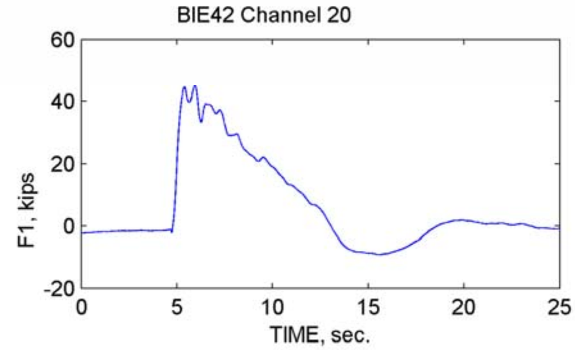

BIE42 Channel 03

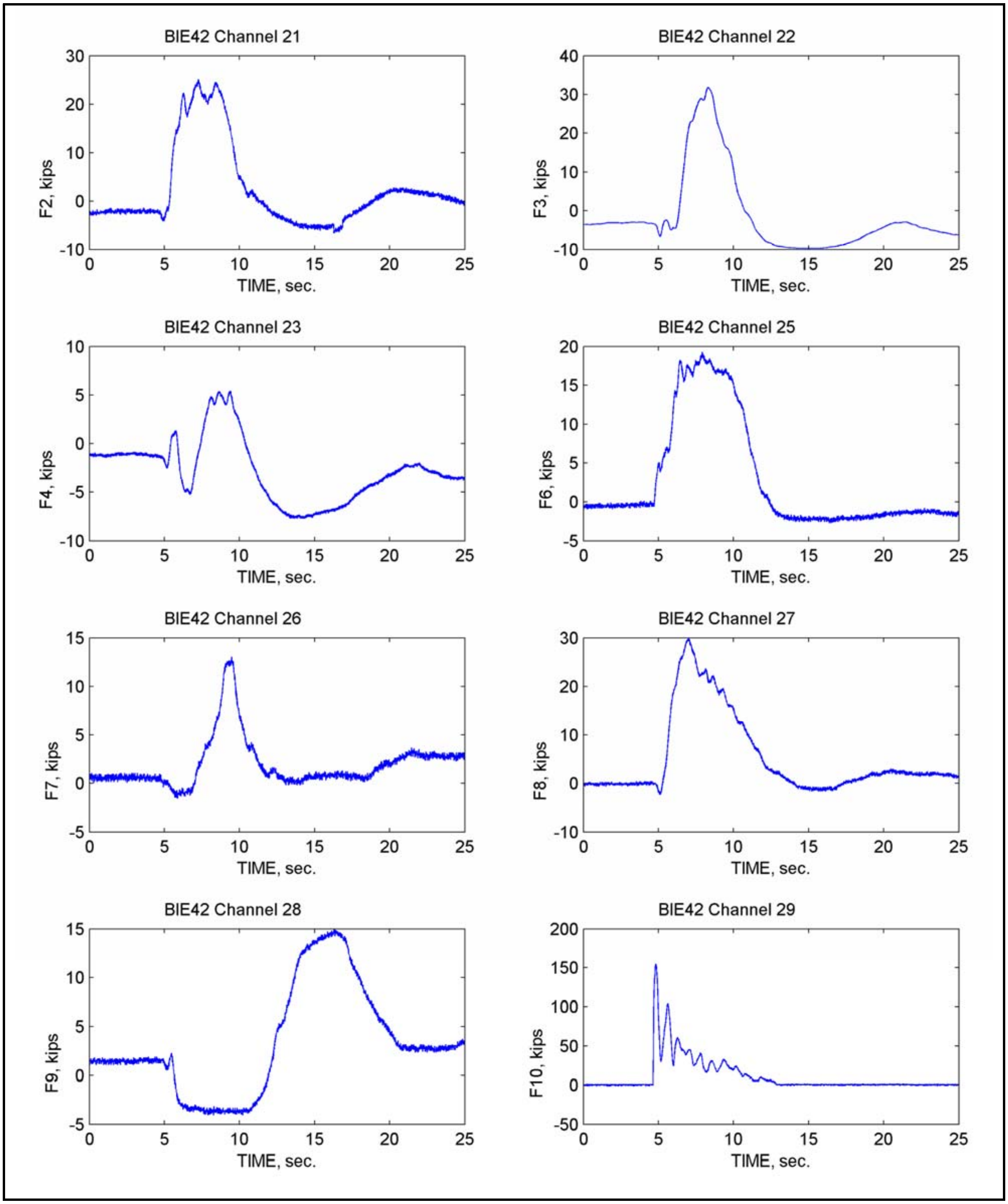

BIE42 Channel 04


BIE42 Channel 05


BIE42 Channel 18


BIE42 Channel 19


BIE42 Channel 20


BIE42 Channel 21

BIE42 Channel 22

BIE42 Channel 23

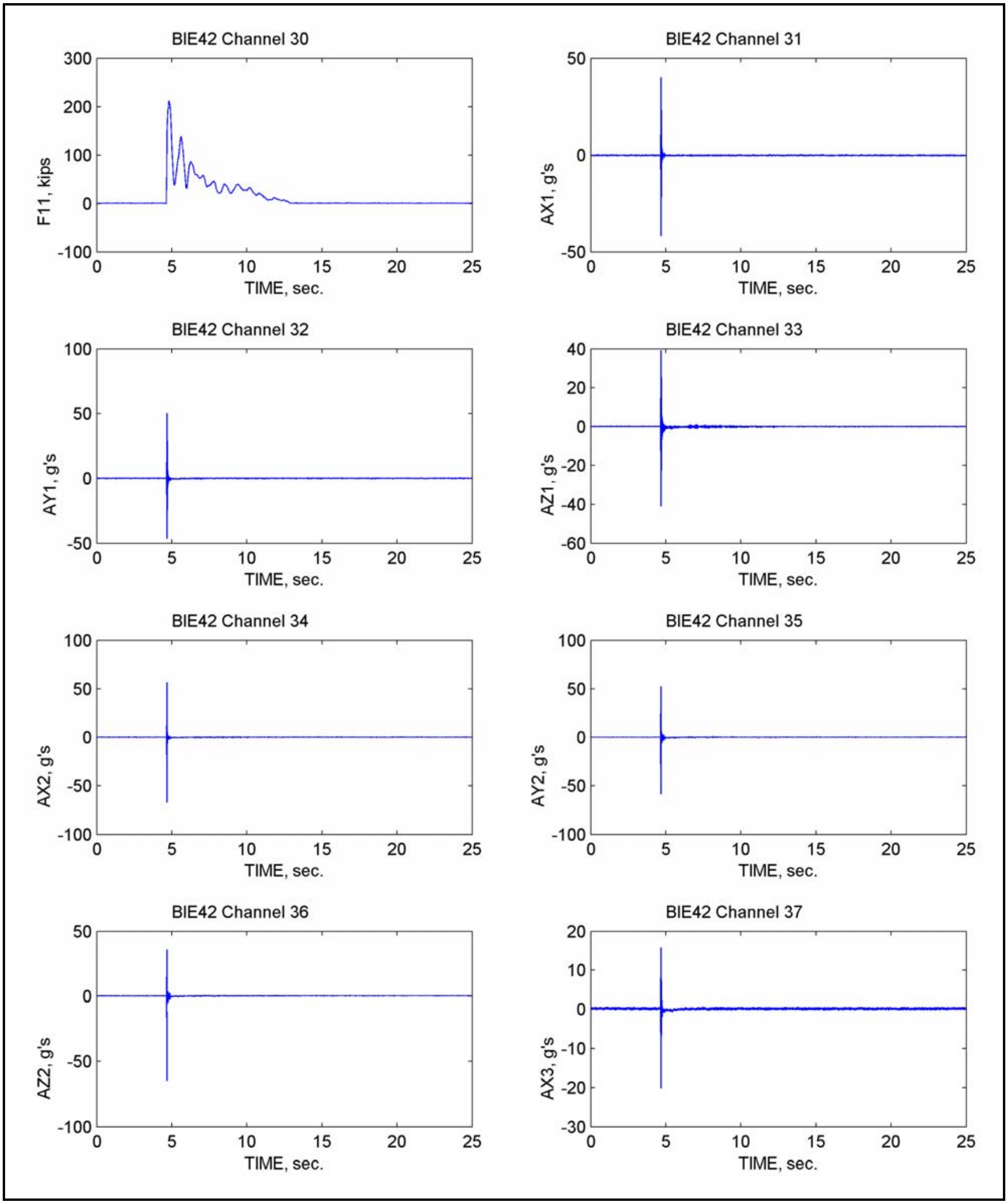
BIE42 Channel 25

BIE42 Channel 26

BIE42 Channel 27

BIE42 Channel 28

BIE42 Channel 29



BIE42 Channel 30

BIE42 Channel 31

BIE42 Channel 32

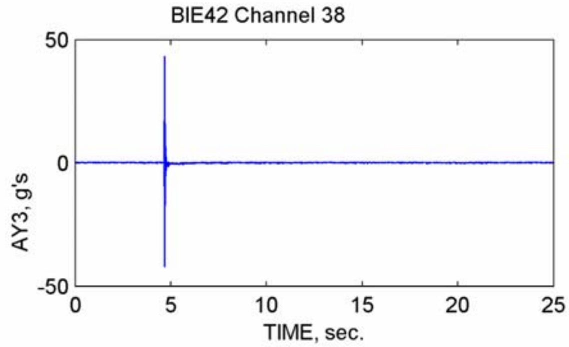
BIE42 Channel 33

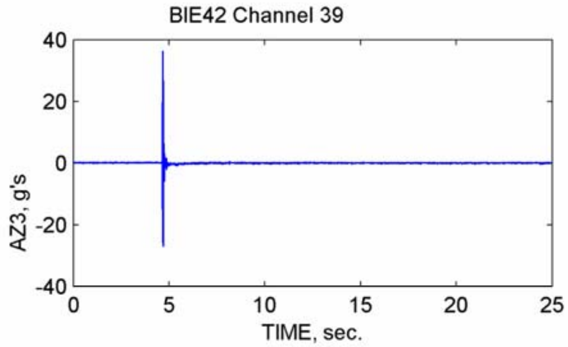
BIE42 Channel 34

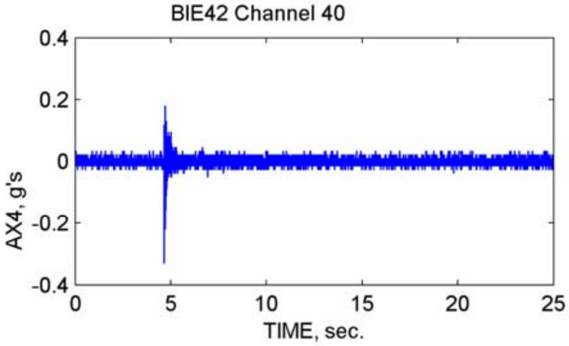
BIE42 Channel 35

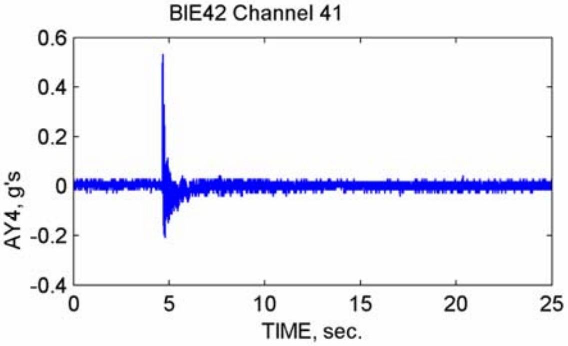
BIE42 Channel 36

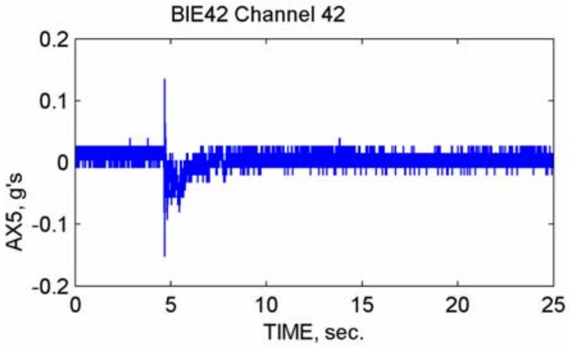
BIE42 Channel 37

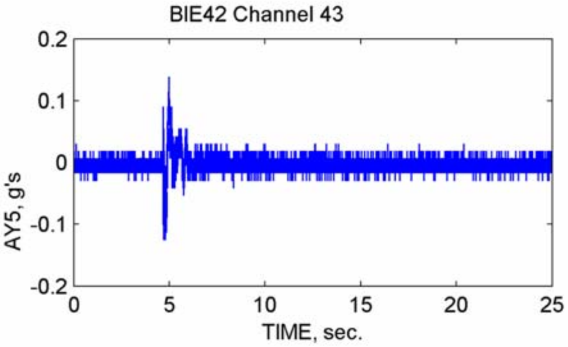

BIE42 Channel 38
AY3, g's
50
0
-50
0
5
10
15
20
25
TIME, sec.

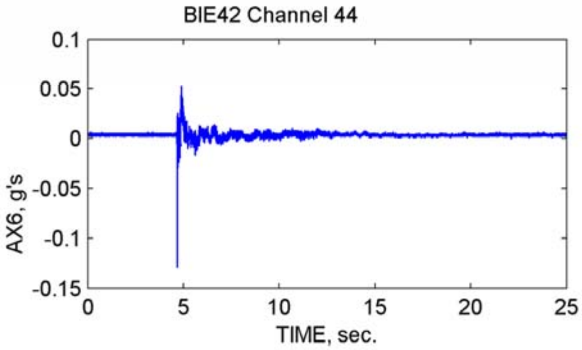

BIE42 Channel 39
AZ3, g's
40
20
0
-20
-40
0
5
10
15
20
25
TIME, sec.

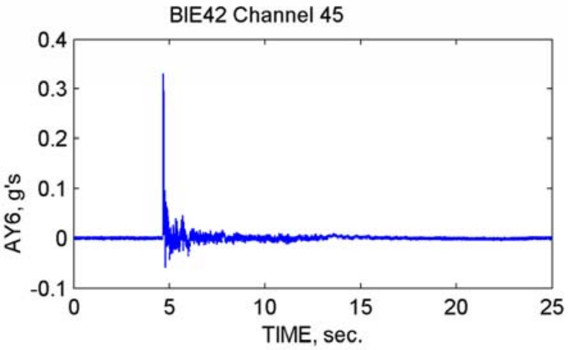

BIE42 Channel 40
AX4, g's
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
TIME, sec.

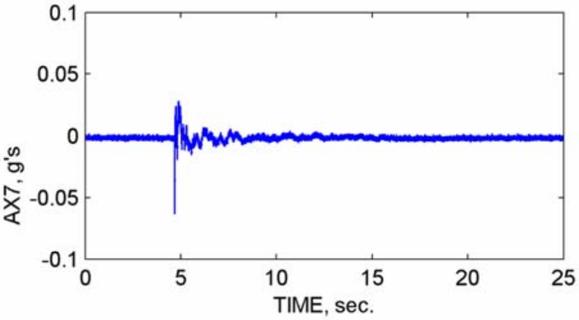

BIE42 Channel 41
AY4, g's
0.6
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
TIME, sec.

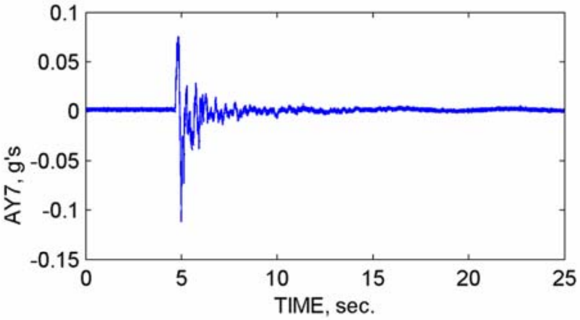

BIE42 Channel 42
AX5, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.

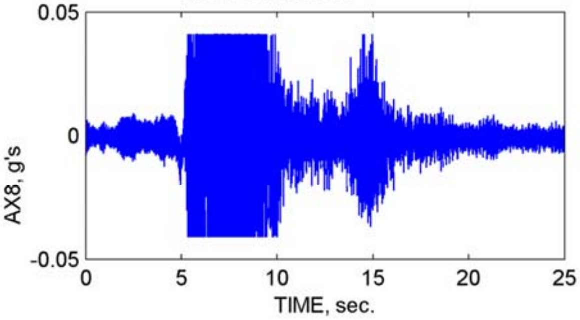

BIE42 Channel 43
AY5, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.

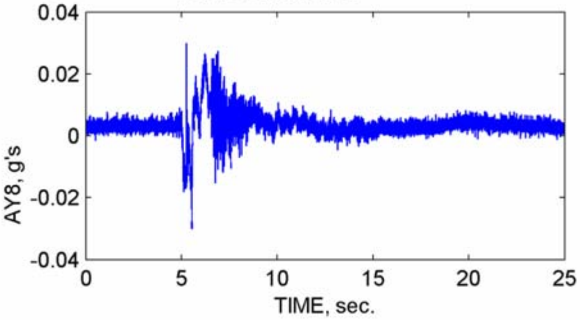

BIE42 Channel 44
AX6, g's
0.1
0.05
0
-0.05
-0.1
-0.15
0
5
10
15
20
25
TIME, sec.

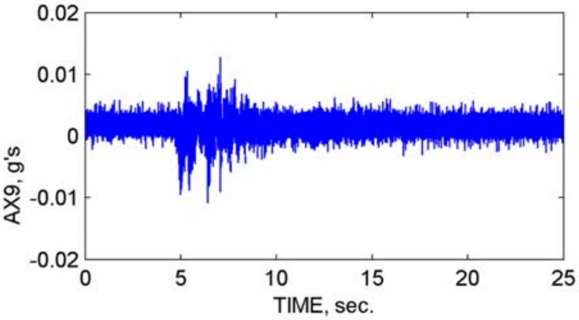

BIE42 Channel 45
AY6, g's
0.4
0.3
0.2
0.1
0
-0.1
0
5
10
15
20
25
TIME, sec.

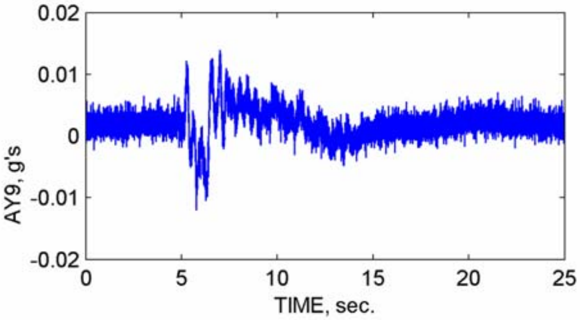

BIE42 Channel 46

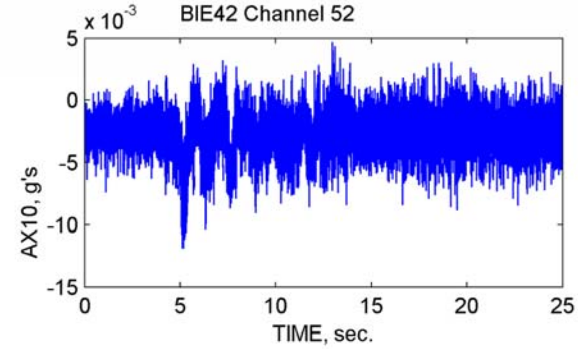

BIE42 Channel 47

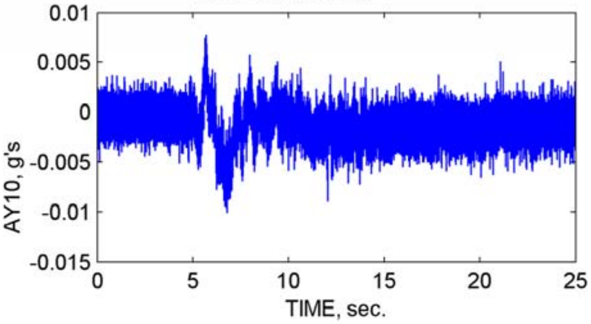

BIE42 Channel 48

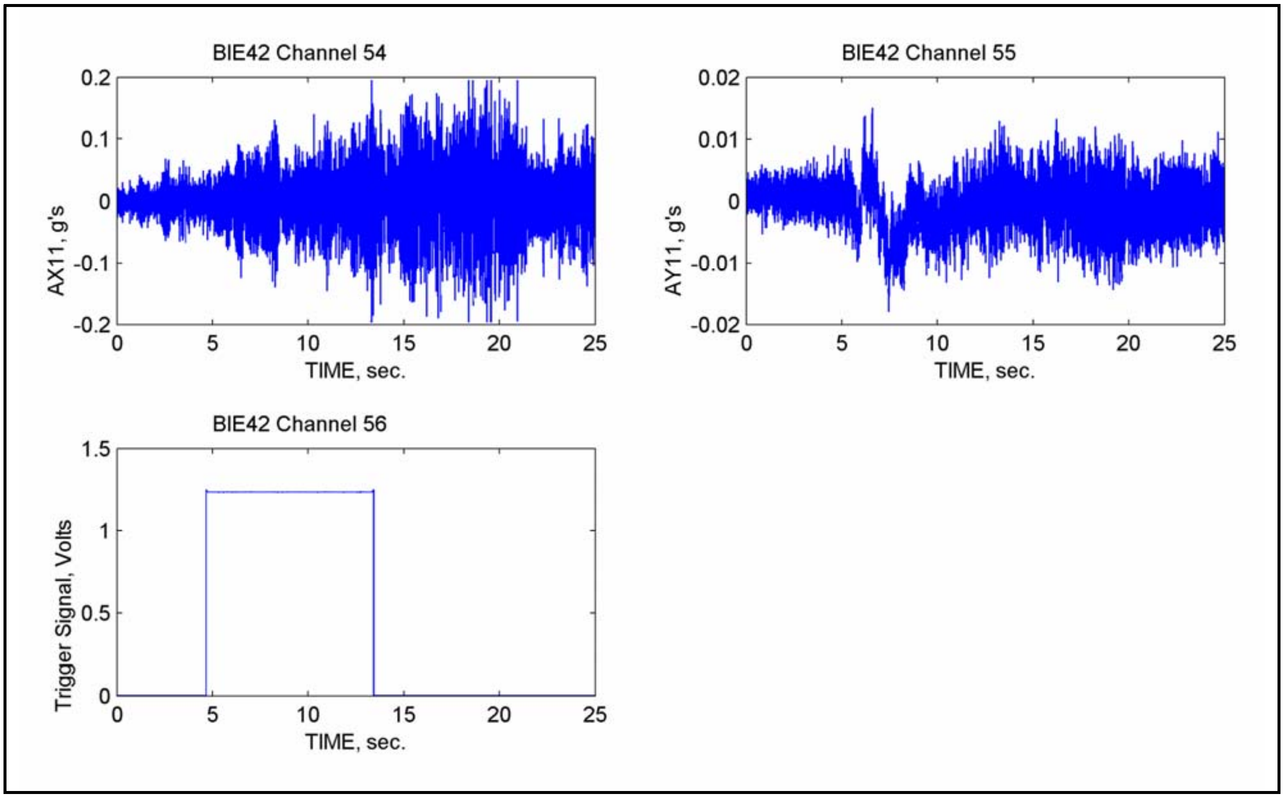

BIE42 Channel 49


BIE42 Channel 50


BIE42 Channel 51


BIE42 Channel 52


BIE42 Channel 53

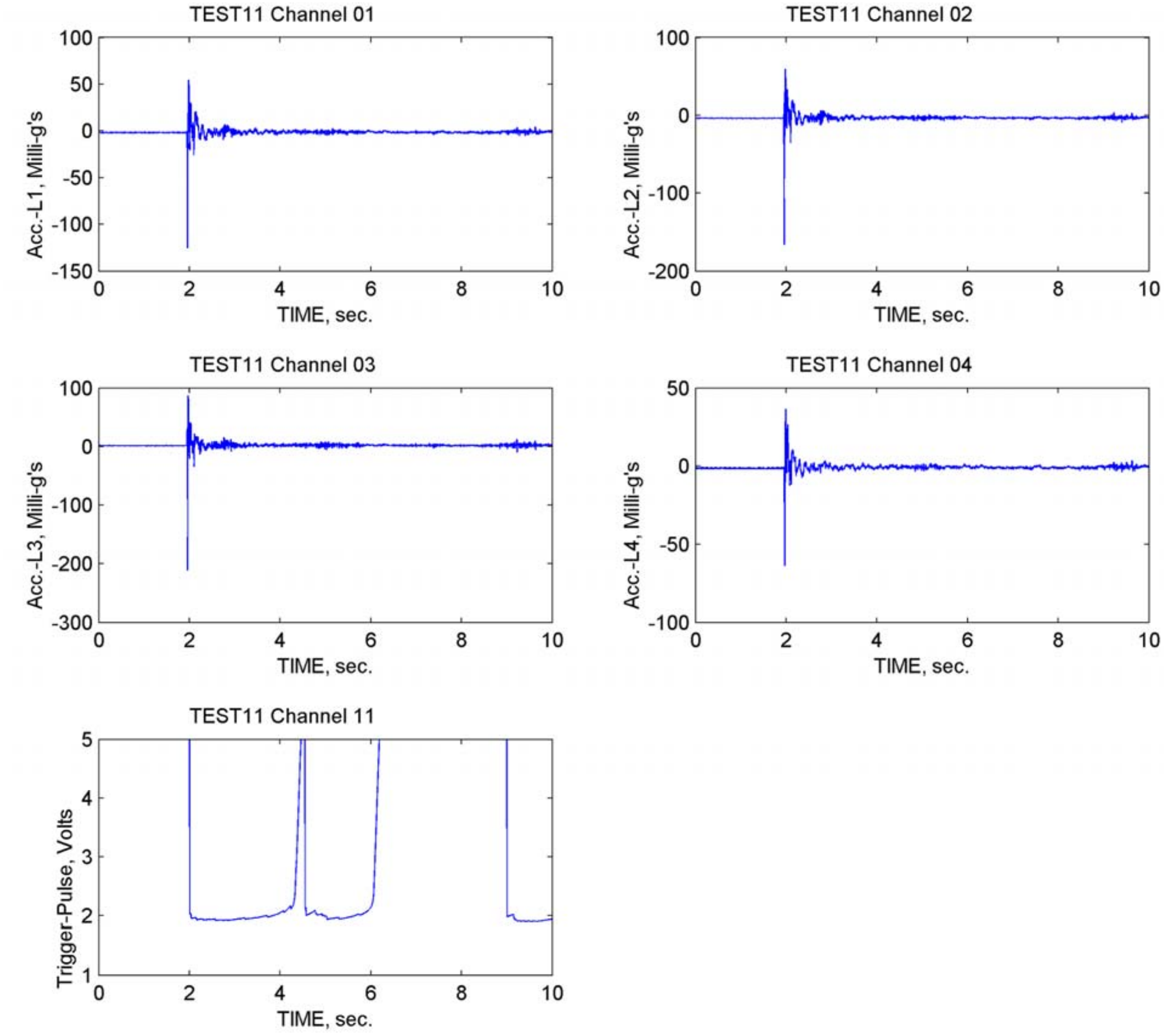

BIE42 Channel 54
AX11, g's
0.2
0.1
0
-0.1
-0.2
0
5
10
15
20
25
TIME, sec.
BIE42 Channel 55
AY11, g's
0.02
0.01
0
-0.01
-0.02
0
5
10
15
20
25
TIME, sec.
BIE42 Channel 56
Trigger Signal, Volts
1.5
1
0.5
0
0
5
10
15
20
25
TIME, sec.

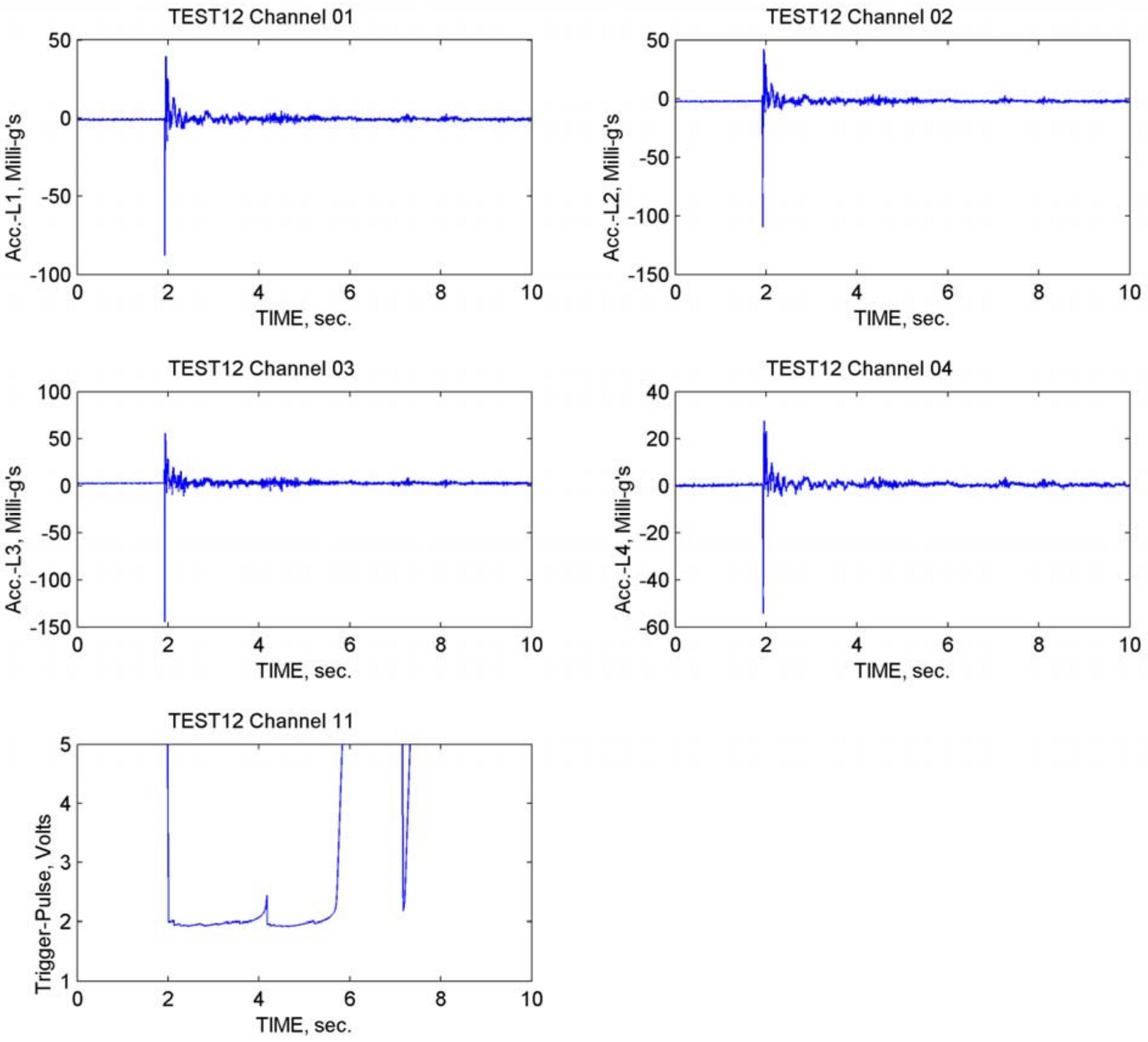
Appendix B
Raw Experiment Data Plots—Lock Wall Instrumentation

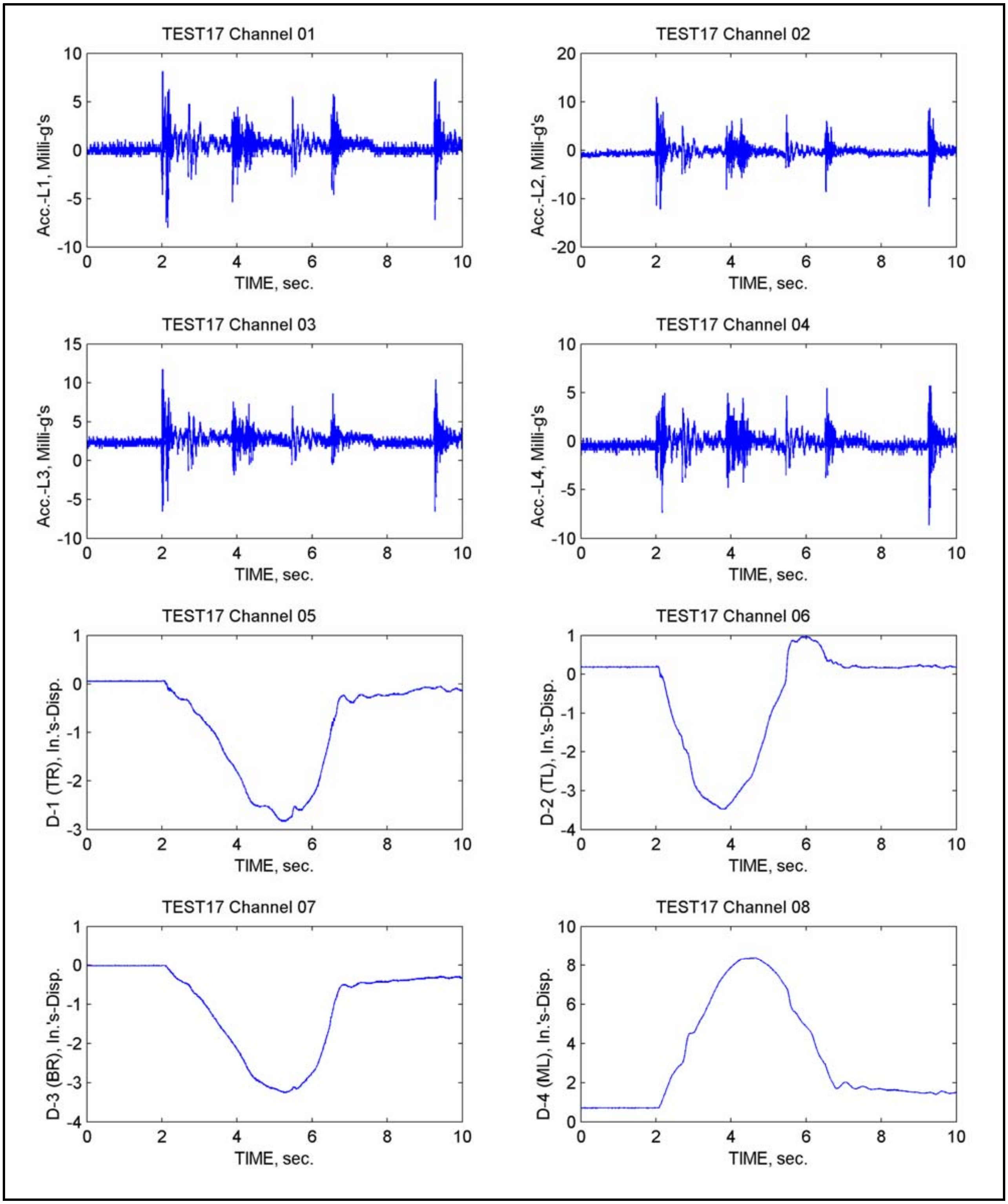
Representative plots of the raw data from the lock wall instrumentation are presented in this report appendix to show the general trends recorded with the data that were collected.

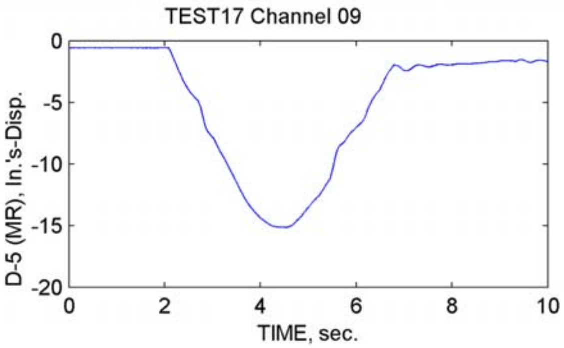
The experiments from which the data plots were derived are indicated. The reference for each instrument (e.g., S1) in each plot can be determined from Tables 5.1-5.4.

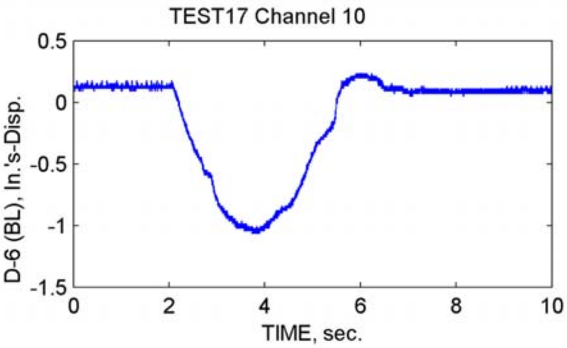
Caveat to the reader: These plots have not been processed in any manner whatsoever. They are purely raw data on scaled plots. Therefore, interpretation and any further use of these data are subject to possible misinterpretation by those unfamiliar with how the data were recorded and the type of instrumentation that was used to collect the data.

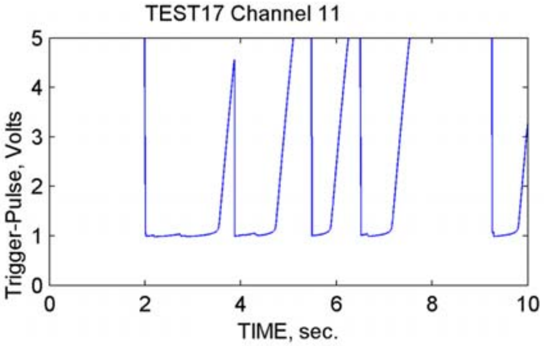

TEST11 Channel 01
Acc.-L1, Milli-g's
100
50
0
-50
-100
-150
TIME, sec.
0
2
4
6
8
10
TEST11 Channel 02
Acc.-L2, Milli-g's
100
0
-100
-200
TIME, sec.
0
2
4
6
8
10
TEST11 Channel 03
Acc.-L3, Milli-g's
100
0
-100
-200
-300
TIME, sec.
0
2
4
6
8
10
TEST11 Channel 04
Acc.-L4, Milli-g's
50
0
-50
-100
TIME, sec.
0
2
4
6
8
10
TEST11 Channel 11
Trigger-Pulse, Volts
5
4
3
2
1
TIME, sec.
0
2
4
6
8
10

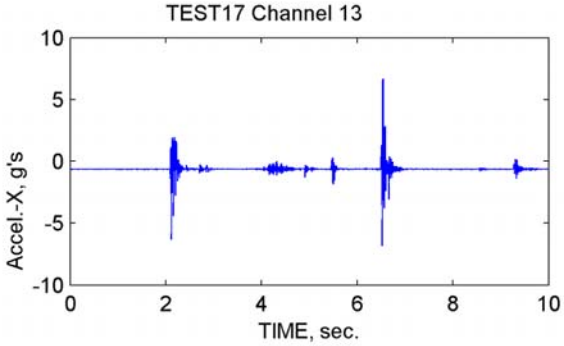

TEST12 Channel 01
Acc.-L1, Milli-g's
50
0
-50
-100
0
2
4
6
8
10
TIME, sec.
TEST12 Channel 02
Acc.-L2, Milli-g's
50
0
-50
-100
-150
0
2
4
6
8
10
TIME, sec.
TEST12 Channel 03
Acc.-L3, Milli-g's
100
50
0
-50
-100
-150
0
2
4
6
8
10
TIME, sec.
TEST12 Channel 04
Acc.-L4, Milli-g's
40
20
0
-20
-40
-60
0
2
4
6
8
10
TIME, sec.
TEST12 Channel 11
Trigger-Pulse, Volts
5
4
3
2
1
0
2
4
6
8
10
TIME, sec.

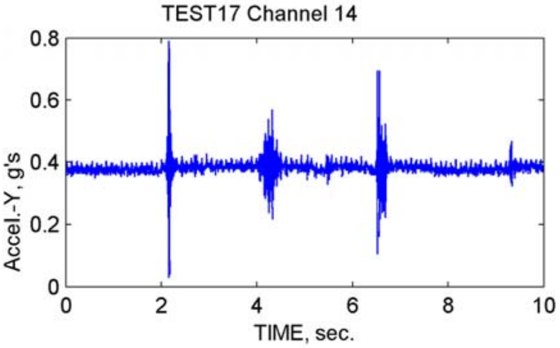

TEST17 Channel 01
Acc.-L1, Milli-g's
10
5
0
-5
-10
0
2
4
6
8
10
TIME, sec.
TEST17 Channel 02
Acc.-L2, Milli-g's
20
10
0
-10
-20
0
2
4
6
8
10
TIME, sec.
TEST17 Channel 03
Acc.-L3, Milli-g's
15
10
5
0
-5
-10
0
2
4
6
8
10
TIME, sec.
TEST17 Channel 04
Acc.-L4, Milli-g's
10
5
0
-5
-10
0
2
4
6
8
10
TIME, sec.
TEST17 Channel 05
D-1 (TR), In.'s-Disp.
1
0
-1
-2
-3
0
2
4
6
8
10
TIME, sec.
TEST17 Channel 06
D-2 (TL), In.'s-Disp.
1
0
-1
-2
-3
-4
0
2
4
6
8
10
TIME, sec.
TEST17 Channel 07
D-3 (BR), In.'s-Disp.
1
0
-1
-2
-3
-4
0
2
4
6
8
10
TIME, sec.
TEST17 Channel 08
D-4 (ML), In.'s-Disp.
10
8
6
4
2
0
0
2
4
6
8
10
TIME, sec.

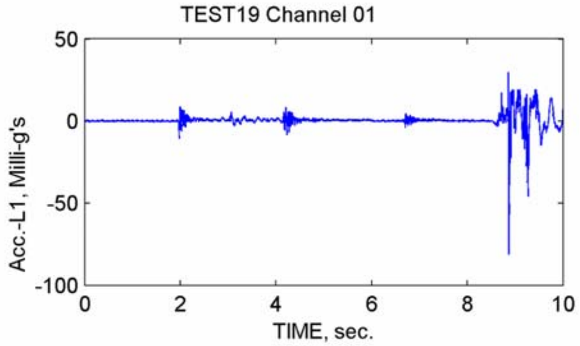

TEST17 Channel 09

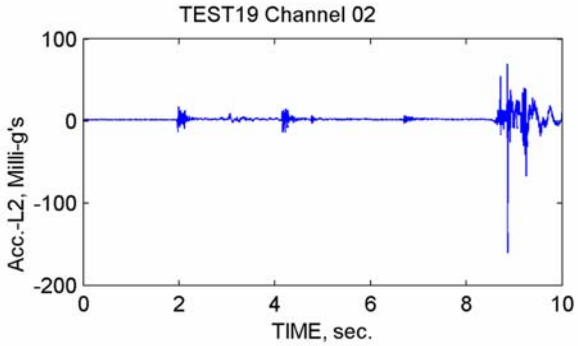

TEST17 Channel 10

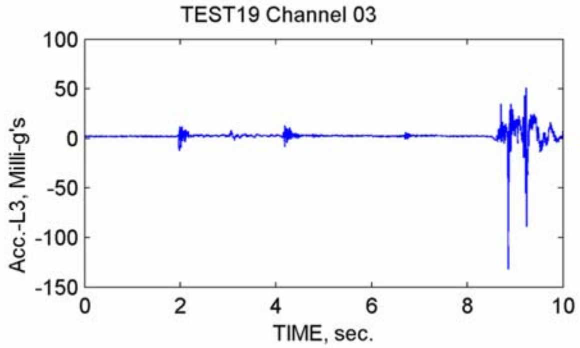

TEST17 Channel 11

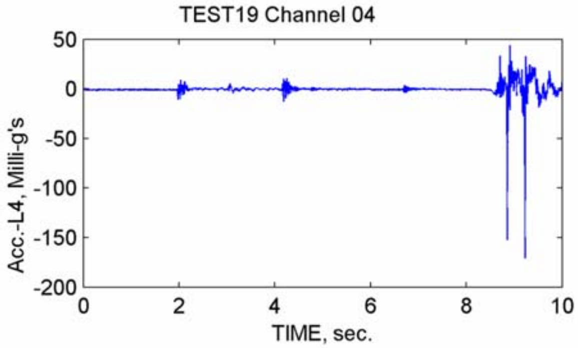

TEST17 Channel 13

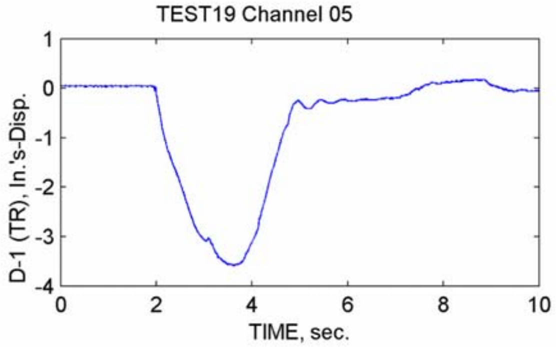

TEST17 Channel 14

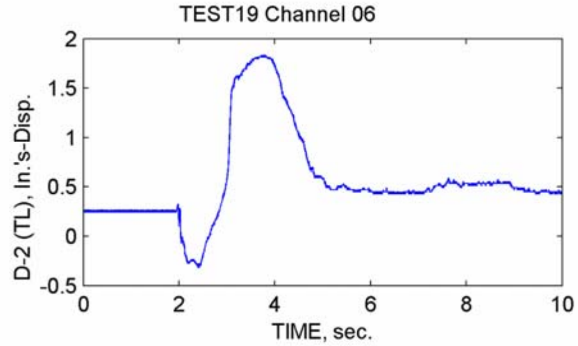

TEST19 Channel 01
Acc.-L1, Milli-g's
50
0
-50
-100
0
2
4
6
8
10
TIME, sec.

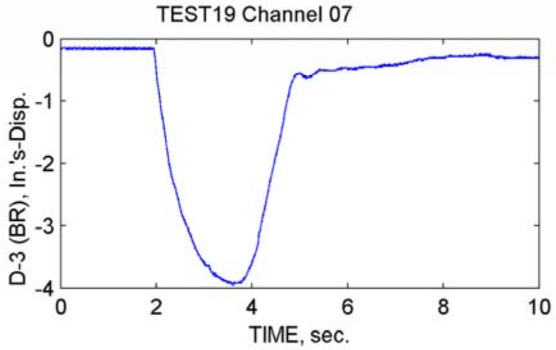

TEST19 Channel 02
Acc.-L2, Milli-g's
100
0
-100
-200
0
2
4
6
8
10
TIME, sec.

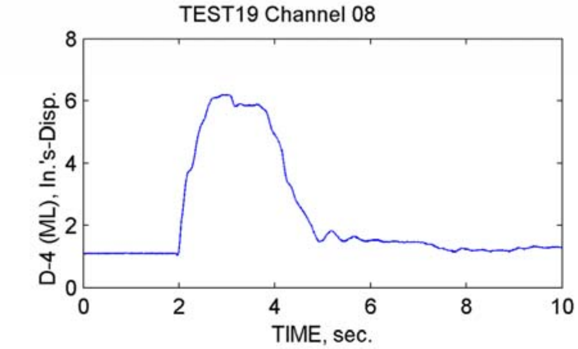

TEST19 Channel 03
Acc.-L3, Milli-g's
100
50
0
-50
-100
-150
0
2
4
6
8
10
TIME, sec.

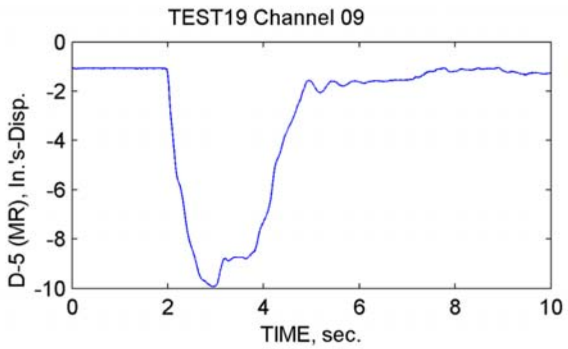

TEST19 Channel 04
Acc.-L4, Milli-g's
50
0
-50
-100
-150
-200
0
2
4
6
8
10
TIME, sec.


TEST19 Channel 05
D-1 (TR), In.'s-Disp.
1
0
-1
-2
-3
-4
0
2
4
6
8
10
TIME, sec.


TEST19 Channel 06
D-2 (TL), In.'s-Disp.
2
1.5
1
0.5
0
-0.5
0
2
4
6
8
10
TIME, sec.


TEST19 Channel 07
D-3 (BR), In.'s-Disp.
0
-1
-2
-3
-4
0
2
4
6
8
10
TIME, sec.


TEST19 Channel 08
D-4 (ML), In.'s-Disp.
8
6
4
2
0
0
2
4
6
8
10
TIME, sec.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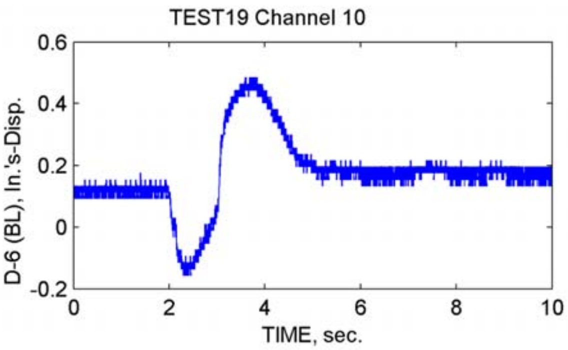
D-5 (MR), In.'s-Disp.
0
-2
-4
-6
-8
-10
0
2
4
6
8
10
TIME, sec.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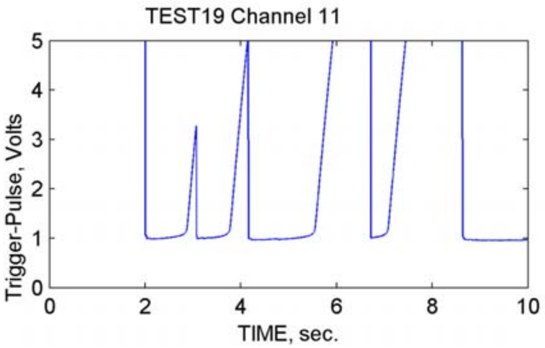
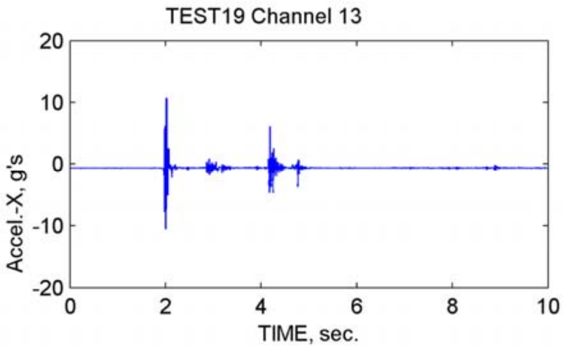
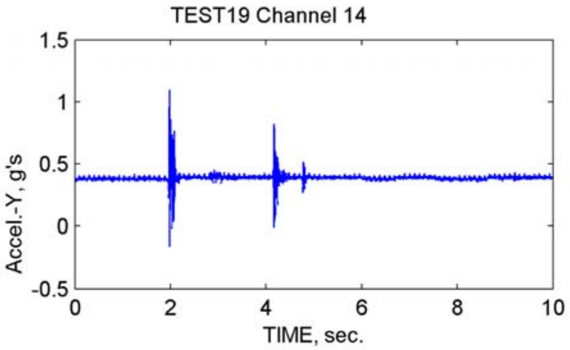
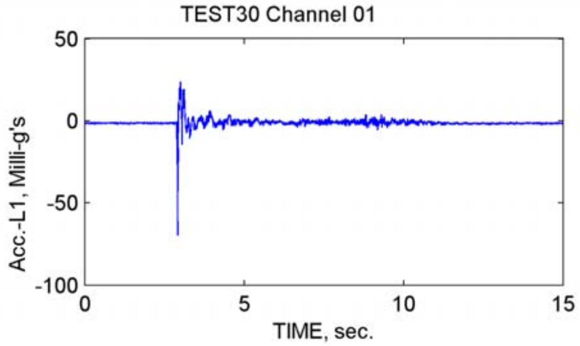
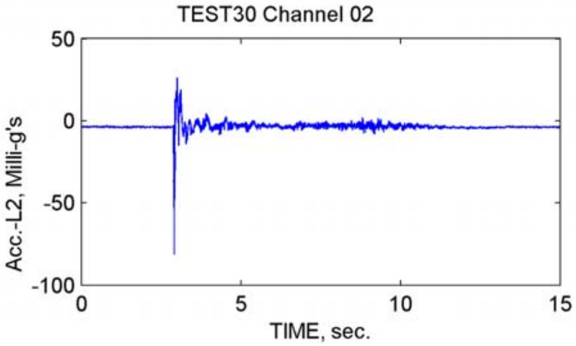
D-6 (BL), In.'s-Disp.
0.6
0.4
0.2
0
-0.2
0
2
4
6
8
10
TIME, sec.

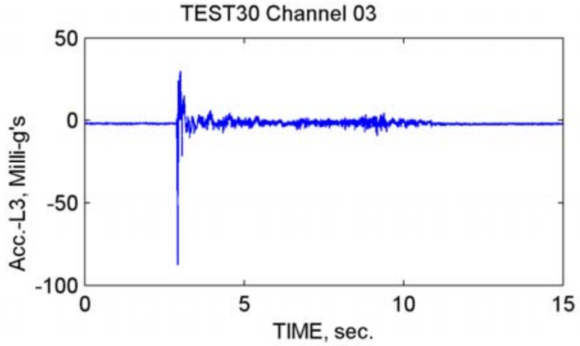

TEST19 Channel 11
Trigger-Pulse, Volts
5
4
3
2
1
0
0
2
4
6
8
10
TIME, sec.


TEST19 Channel 13
Accel.-X, g's
20
10
0
-10
-20
0
2
4
6
8
10
TIME, sec.


TEST19 Channel 14
Accel.-Y, g's
1.5
1
0.5
0
-0.5
0
2
4
6
8
10
TIME, sec.


TEST30 Channel 01


TEST30 Channel 02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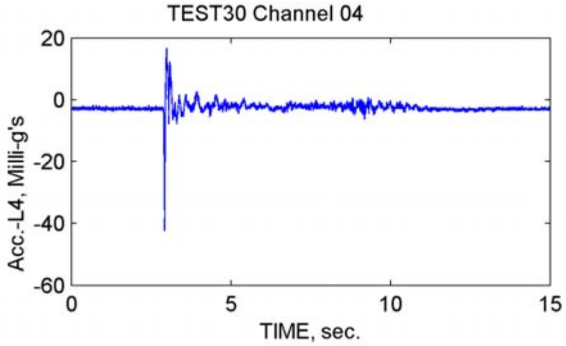
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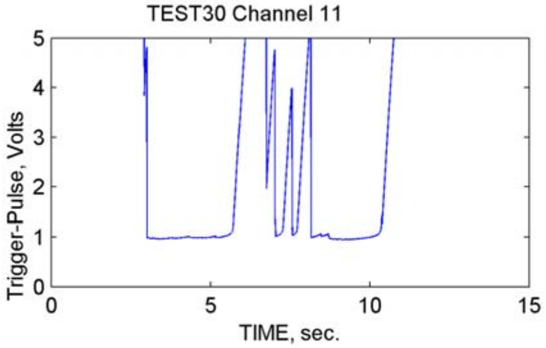
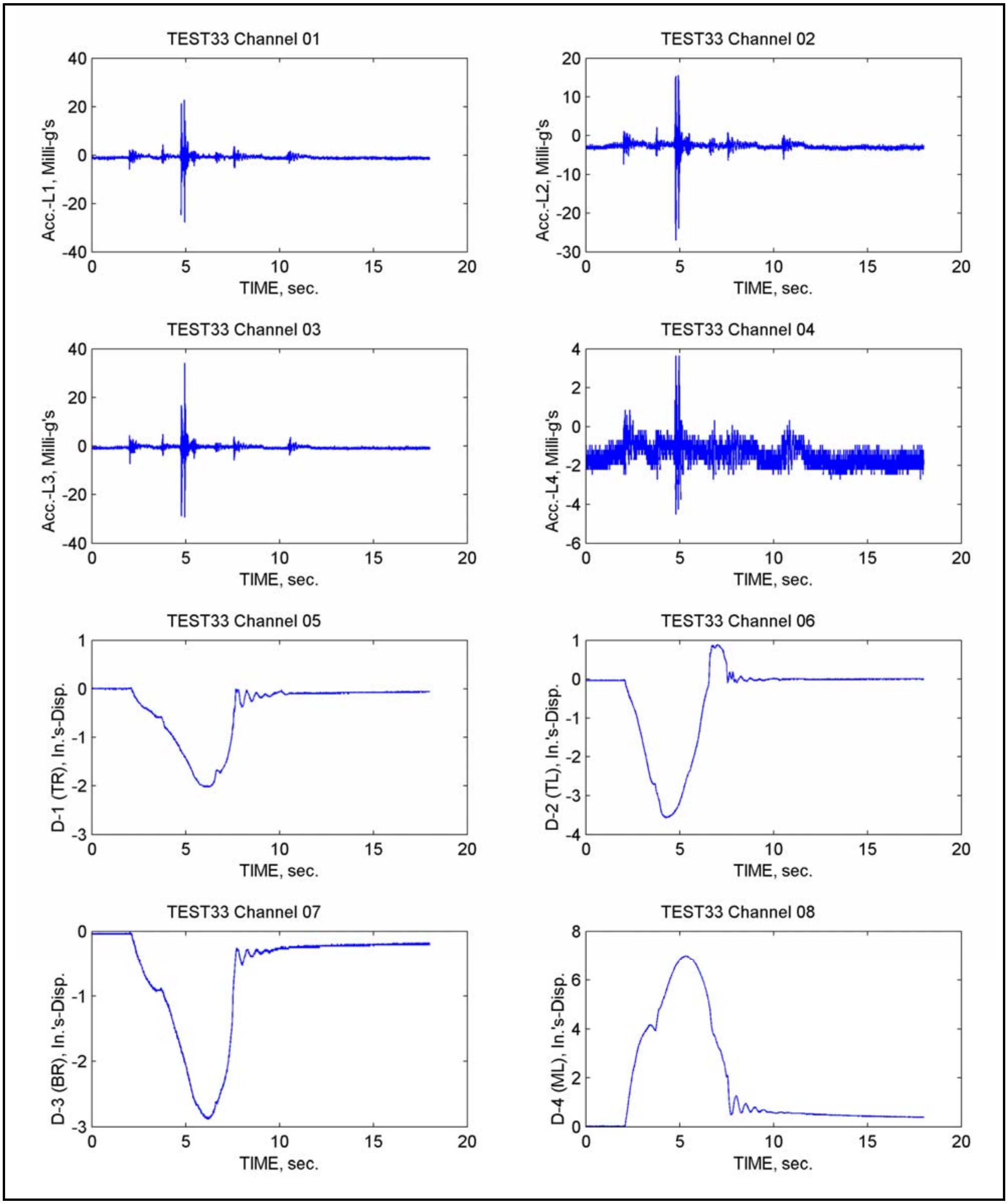
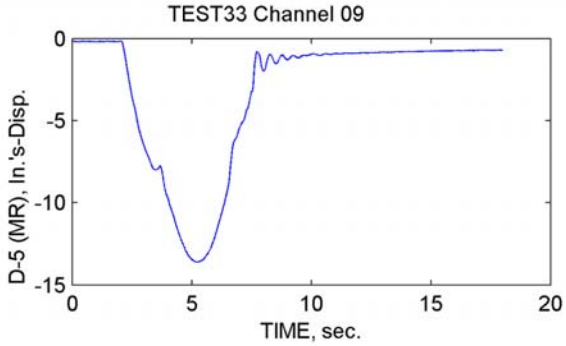

TEST30 Channel 11


TEST33 Channel 01
Acc.-L1, Milli-g's
40
20
0
-20
-40
TIME, sec.
0
5
10
15
20
TEST33 Channel 02
Acc.-L2, Milli-g's
20
10
0
-10
-20
-30
TIME, sec.
TEST33 Channel 03
Acc.-L3, Milli-g's
TIME, sec.
TEST33 Channel 04
Acc.-L4, Milli-g's
4
2
0
-2
-4
-6
TIME, sec.
TEST33 Channel 05
D-1 (TR), In.'s-Disp.
1
0
-1
-2
-3
TIME, sec.
TEST33 Channel 06
D-2 (TL), In.'s-Disp.
1
0
-1
-2
-3
-4
TIME, sec.
TEST33 Channel 07
D-3 (BR), In.'s-Disp.
0
-1
-2
-3
TIME, sec.
TEST33 Channel 08
D-4 (ML), In.'s-Disp.
8
6
4
2
0
TIME, sec.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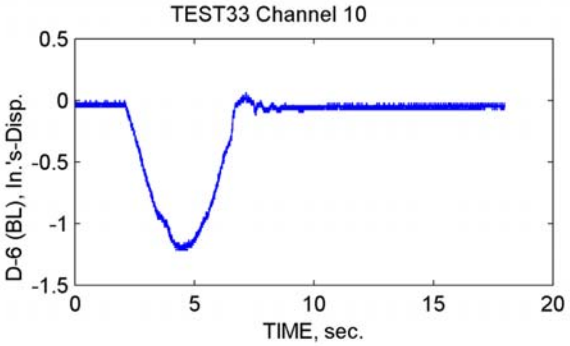
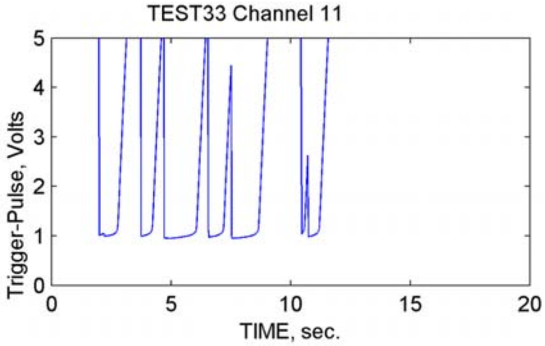
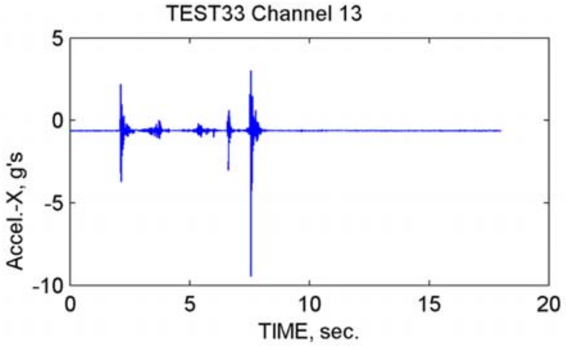
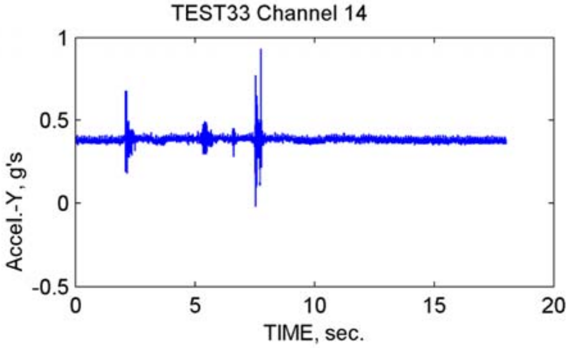

TEST33 Channel 10


TEST33 Channel 11


TEST33 Channel 13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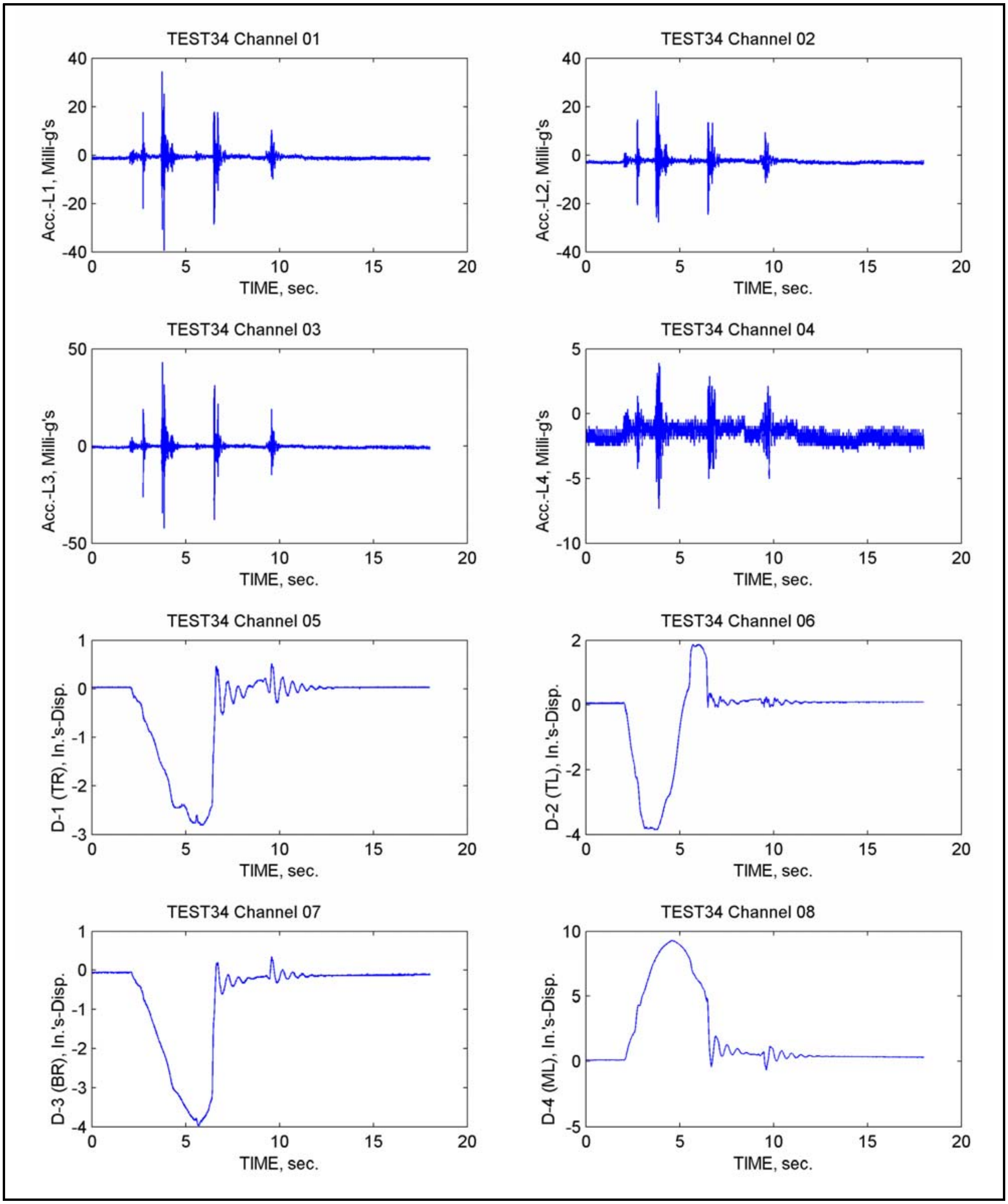
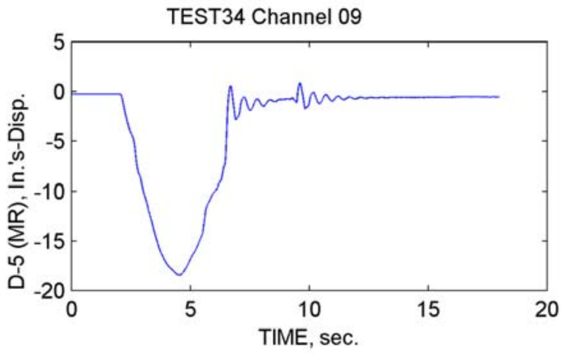
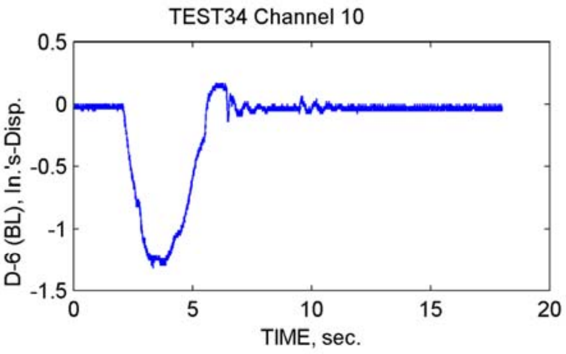
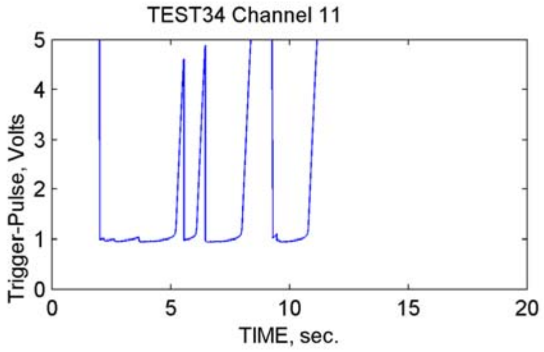
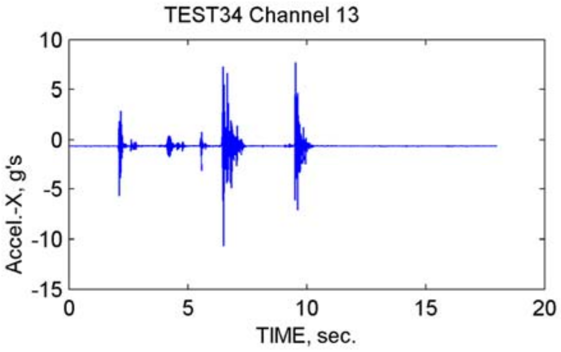
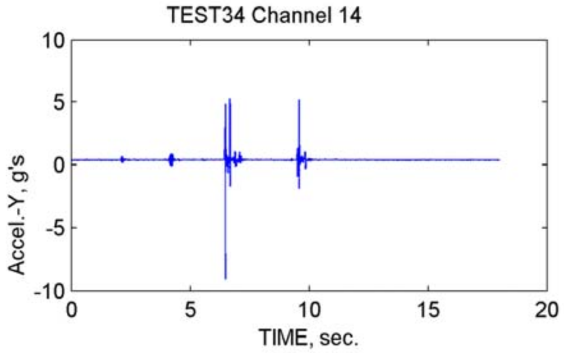

TEST34 Channel 01
Acc.-L1, Milli-g's
40
20
0
-20
-40
0
5
10
15
20
TIME, sec.
TEST34 Channel 02
Acc.-L2, Milli-g's
40
20
0
-20
-40
0
5
10
15
20
TIME, sec.
TEST34 Channel 03
Acc.-L3, Milli-g's
50
0
-50
0
5
10
15
20
TIME, sec.
TEST34 Channel 04
Acc.-L4, Milli-g's
5
0
-5
-10
0
5
10
15
20
TIME, sec.
TEST34 Channel 05
D-1 (TR), In.'s-Disp.
1
0
-1
-2
-3
0
5
10
15
20
TIME, sec.
TEST34 Channel 06
D-2 (TL), In.'s-Disp.
2
0
-2
-4
0
5
10
15
20
TIME, sec.
TEST34 Channel 07
D-3 (BR), In.'s-Disp.
1
0
-1
-2
-3
-4
0
5
10
15
20
TIME, sec.
TEST34 Channel 08
D-4 (ML), In.'s-Disp.
10
5
0
-5
0
5
10
15
20
TIME, sec.

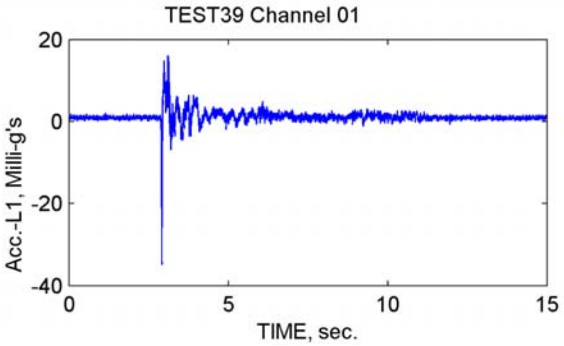

TEST34 Channel 09
D-5 (MR), In.'s-Disp.
5
0
-5
-10
-15
-20
0
5
10
15
20
TIME, sec.


TEST34 Channel 10
D-6 (BL), In.'s-Disp.
0.5
0
-0.5
-1
-1.5
0
5
10
15
20
TIME, sec.


TEST34 Channel 11
Trigger-Pulse, Volts
5
4
3
2
1
0
0
5
10
15
20
TIME, sec.


TEST34 Channel 13
Accel.-X, g's
10
5
0
-5
-10
-15
0
5
10
15
20
TIME, sec.


TEST34 Channel 14
Accel.-Y, g's
10
5
0
-5
-10
0
5
10
15
20
TIME, sec.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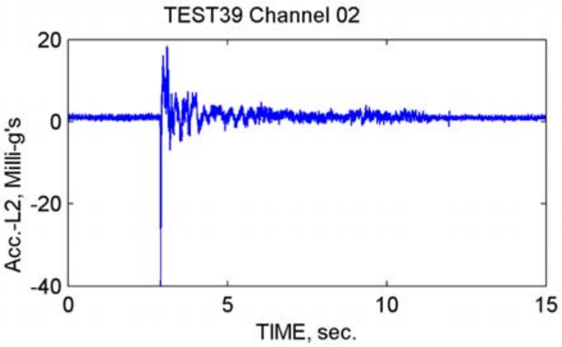
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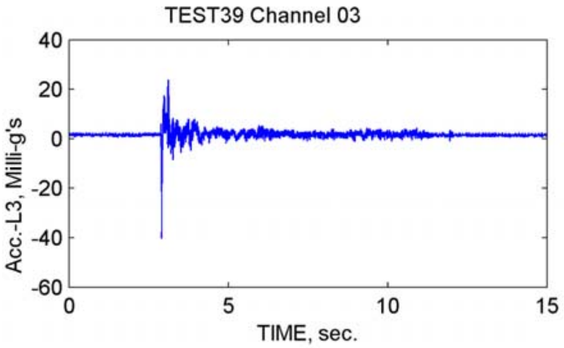
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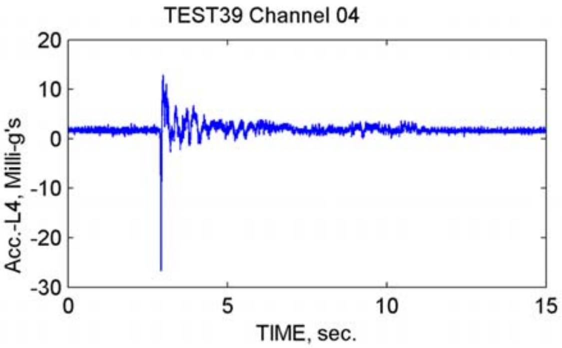
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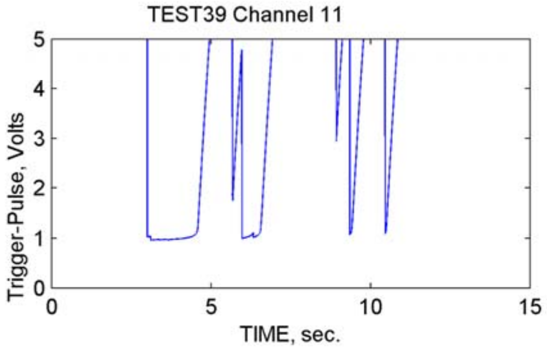
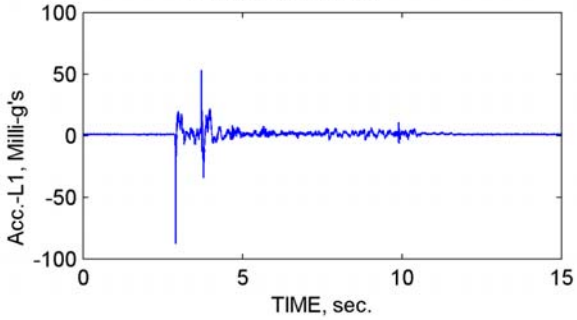
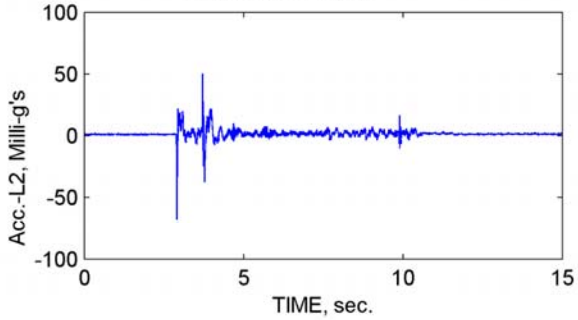

TEST39 Channel 11


TEST40 Channel 01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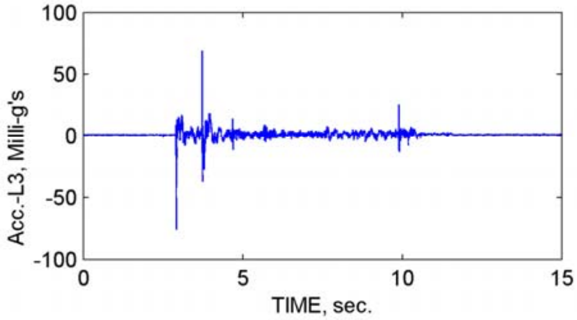
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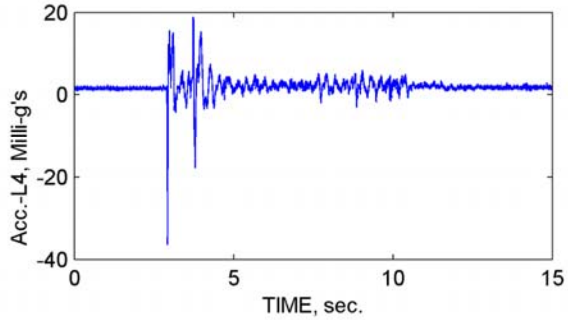
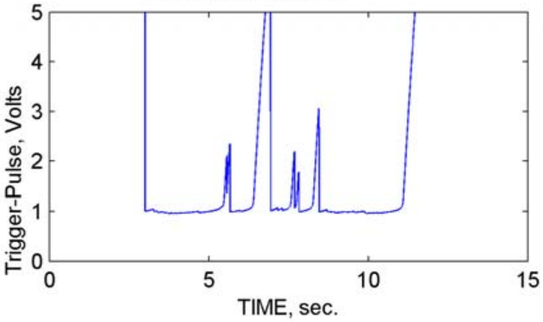

TEST40 Channel 04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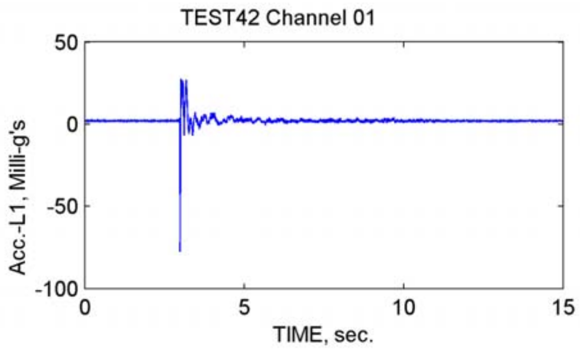
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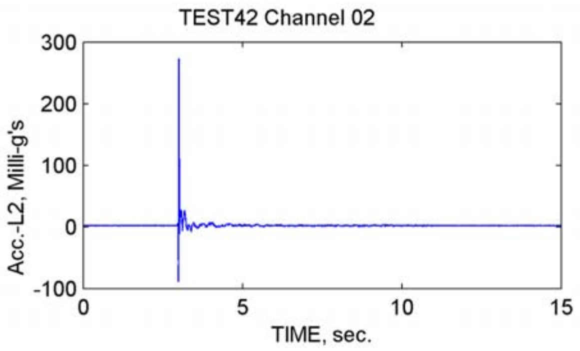
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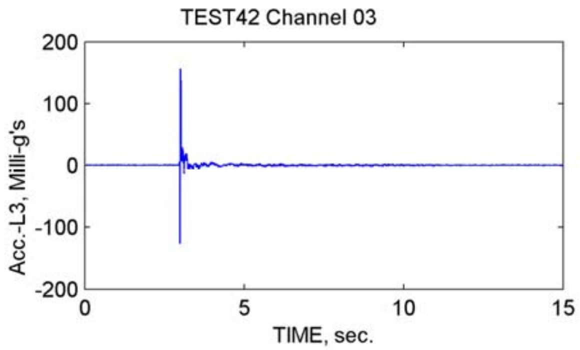
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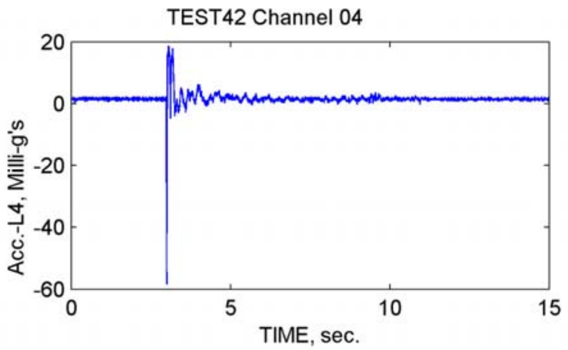
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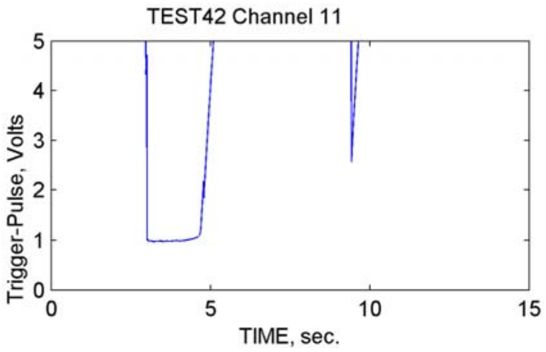
TEST42 Channel 11

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14. ABSTRACT

Full-scale barge impact experiments were conducted on a rigid upstream guide wall at Robert C. Byrd Lock and Dam (Old Gallipolis Lock) in Gallipolis Ferry, WV. The primary goal of these experiments was to measure the actual impact forces normal to the wall using a load-measuring device. Additional objectives of these experiments were to obtain and measure the baseline response of an inland waterway barge, quantify a multi-degree-of-freedom system during impact, and investigate the use of energy-absorbing fenders. The full-scale experiments used a 15-barge commercial flotilla. The barges were jumbo open-hopper rake barges (35 by 195 ft; 11 by 59 m) and were ballasted with coal to a draft of 9 ft (2.5 m). The total mass of the flotilla was approximately 27,000 metric tons.

Instrumentation similar to that used during the "prototype" experiments, performed in August 1998, was used for the full-scale experiments. This included accelerometers, strain gages, and clevis pin load cells in the lashing parts. The instrumentation data were collected using over 80 channels of instrumentation on both the barge and lock wall. These experiments also utilized a differential global positioning system (DGPS) on the flotilla to measure the tow velocity, angle, and rotation during impact, as well as high-speed cameras to capture the barge-wall and barge-fender interaction.

(Continued)

15. SUBJECT TERMS

Barge(s)	Clevis pin	Full-scale experiments
Barge impact	Fendering systems	Impact angles
	Flotilla	Impact velocities

(Continued)

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Prescribed by ANSI Std. 239.18

14. (Concluded)

New state-of-the-art instrumentation was developed to measure the actual load normal to the barge and wall. This consisted of a load-measuring beam that had two clevis pin load cells capable of measuring up to approximately 1,200 kips (5,340 kN). In addition, a system of polyvinylidene fluoride (PVDF) sensors was developed at the U.S. Army Engineer Research and Development Center as part of a redundant load-measurement system on the load beam.

Forty-four impact experiments were successfully conducted on both the rigid concrete upper guide wall (baseline and load-measuring device) and on the prototype fendering system (baseline and load-measuring device). A matrix of the required angles and velocities was assembled for the comparison between the baseline and load-measuring experiments on both the concrete and prototype fendering systems. This matrix was successfully filled for each impact case during these 44 experiments. The final matrix contained angles of impact from 5 to 25 deg, with velocities from 0.5 to 4 ft (0.15 to 1.2 m) per second.

The report includes detailed explanations of the instrumentation used, including data acquisition systems, barge and lock wall instrumentation, DGPS, and high-speed camera and videotape equipment. Design concepts and installation of the prototype fendering system used in the experiments are also discussed. Conclusions and recommendations are presented, in support of the future numerical modeling and data interpretation efforts. Appendixes to the report present a selected collection of raw data plots from the baseline and load beam experiments.

15. (Concluded)

Inland waterway
Instrumentation
Load beam
Load measuring
Lock walls
Towboat(s)
Vessel impact