Borehole Accelerometers

Avery "Zack" Cashion

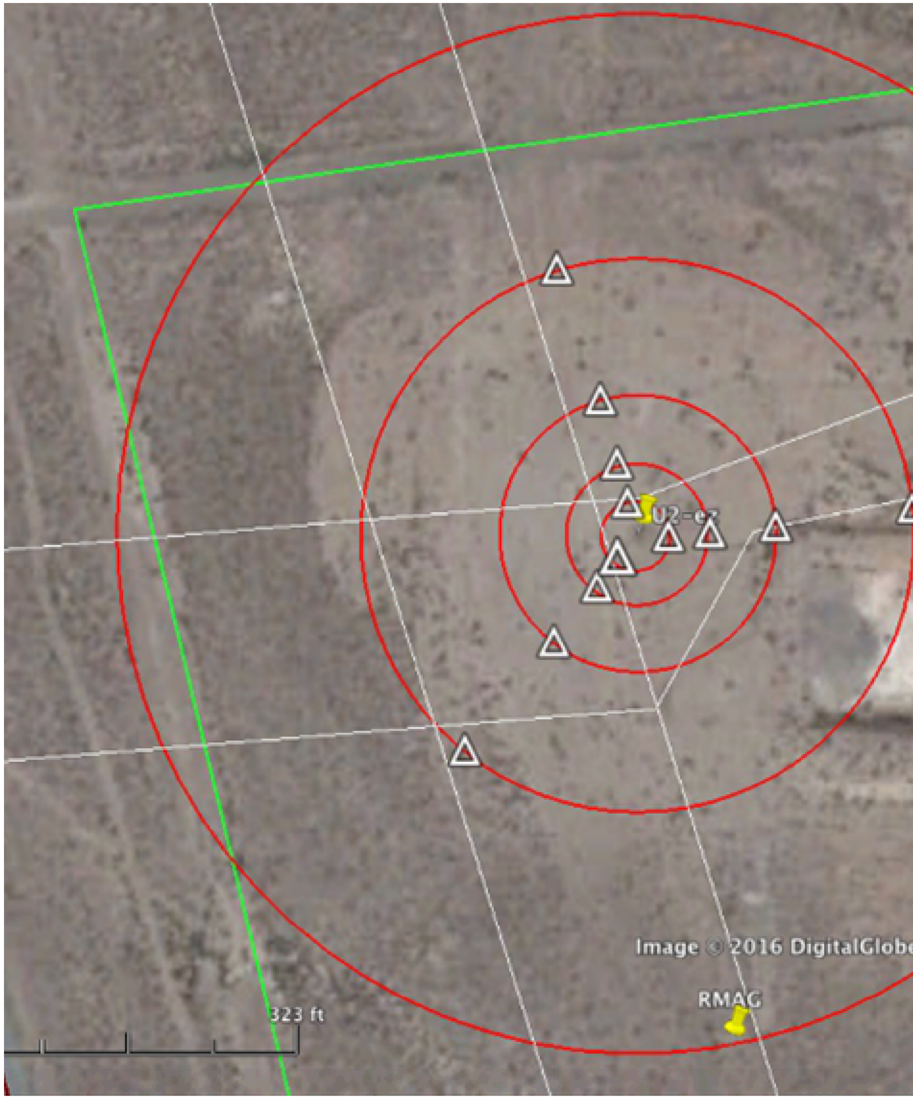
09/12/2017

SAND2017-9815PE

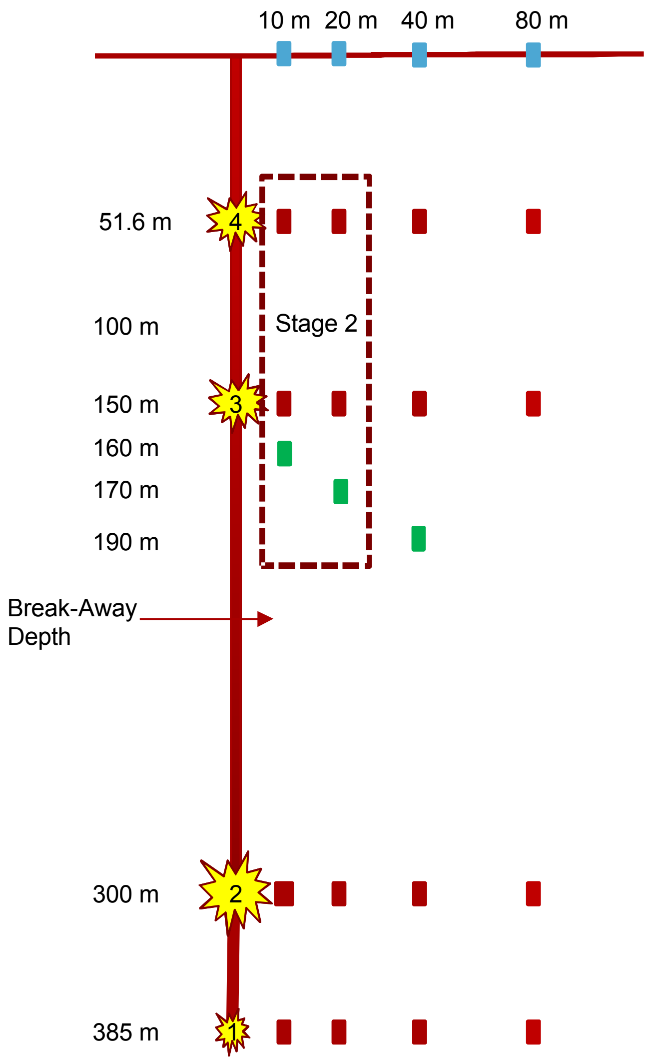
Outline

- System Design Description
- Readiness
- Risk
- Operations
- Post-Shot Deliverables
- Lessons Learned
- Next Steps

BH Locations and Drilling Plan



BH Name	Lat	Long	Depth of Hole (ft)
N10	37.114736°	-116.069307°	1297
N20	37.114837°	-116.069342°	1297
N40	37.115002°	- 116.069396°	1297
N80	37.115342°	-116.069537°	1297
E10	37.114649°	-116.069174°	1297
E20	37.114658°	-116.069038°	1297
E40	37.114674°	-116.068824°	1297
E80	37.114722°	-116.068378°	1297
SW10	37.114594°	-116.069340°	1297
SW20	37.114516°	-116.069406°	1297
SW40	37.114374°	-116.069547°	1297
SW80	37.114092°	-116.069837°	To Basement*



Final depth of DAG-1 shot and accelerometers TBD, but holes were drilled to 1297'

Red pods are designed to measure the shot at that level.
Green pods are designed to measure DAG 3 and DAG 4.

Accelerometer Predictions (g) Perrett & Bass Dry Alluvium				
Depth of Pod (m)	**R=10**	**R=20**	**R=40**	**R=80**
51.6	709.461	13.193	2.639	0.970
150	709.461	13.193	2.639	0.970
300	9217.657	171.404	4.839	1.779
385	18.097	7.788	1.109	0.407

Depth of Pod (m)	**160**	**170**	**190**
DAG-1	0.045	0.049	0.058
DAG-2	0.529	0.607	0.778
DAG-3	131.440	9.370	2.085
DAG-4	0.517	0.419	0.283

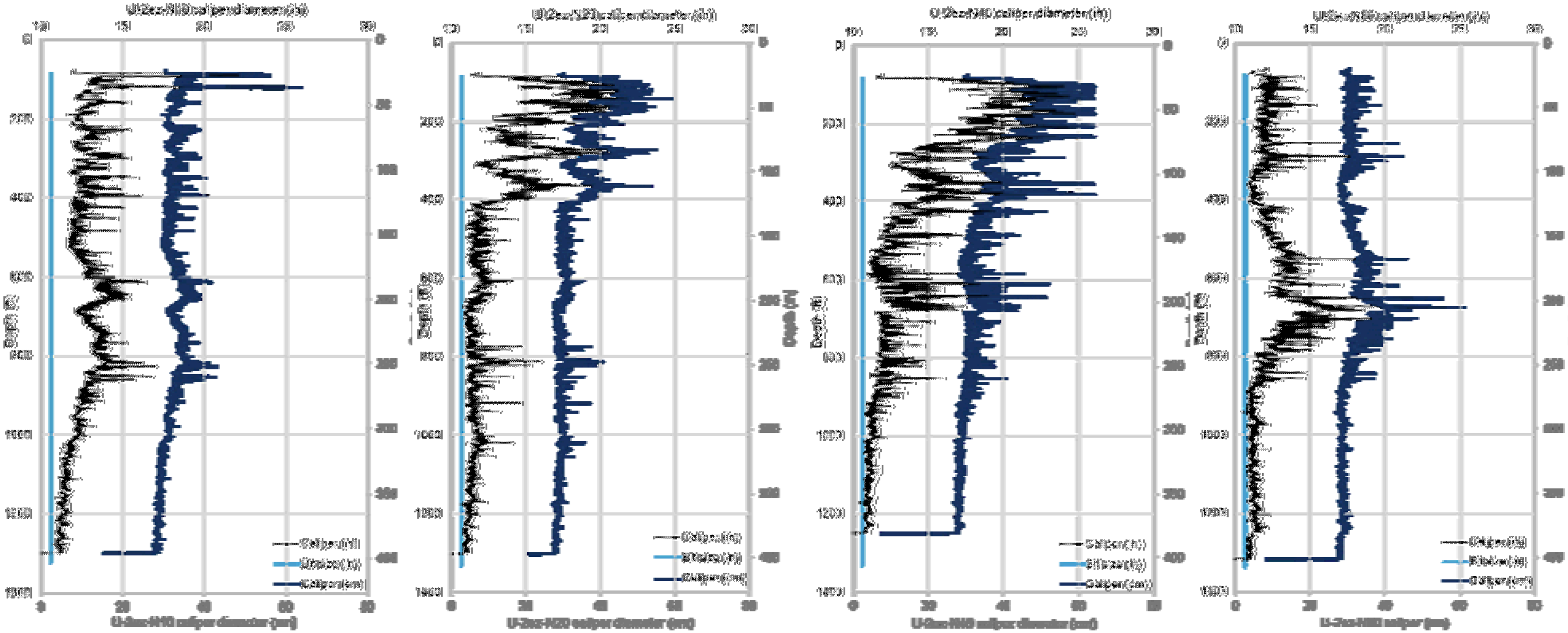
DAG-1 and DAG-2 not required for these instruments but estimates show the same accelerometers should work.

Hole Depths

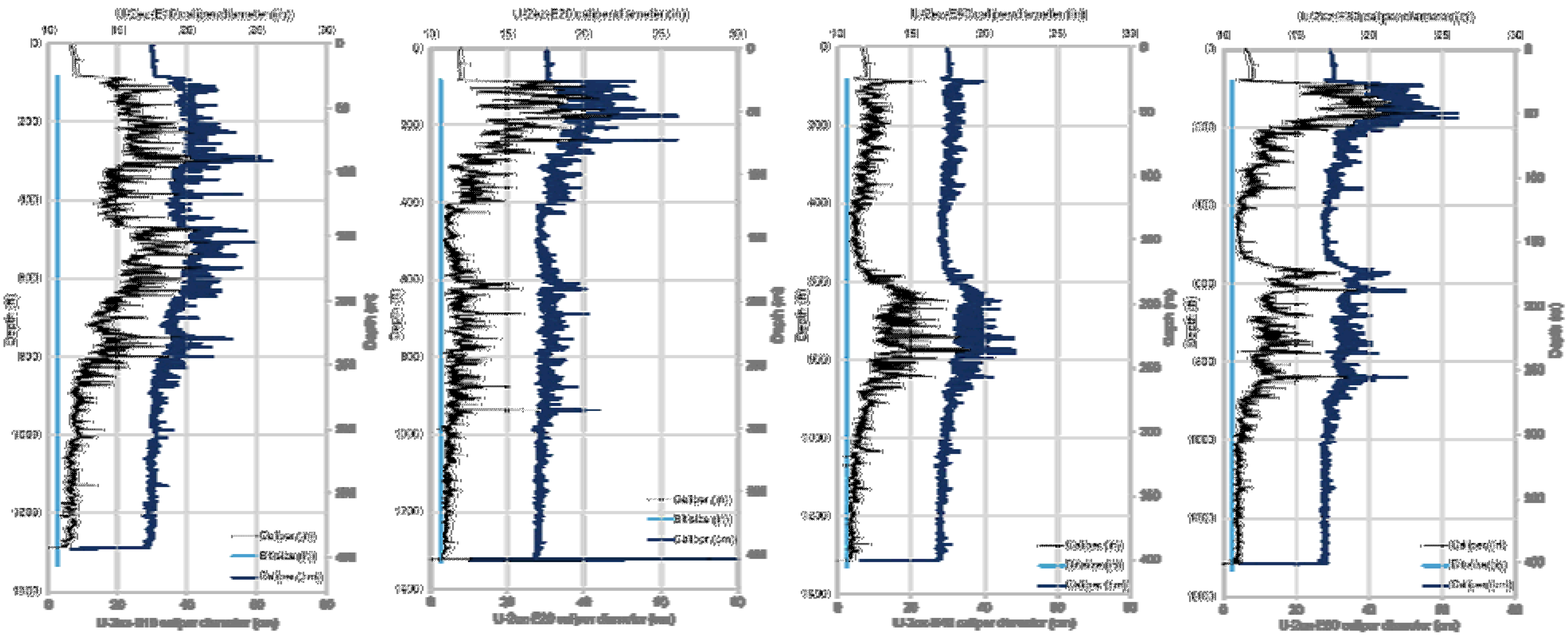
Borehole	Drilled (ft)	Drilled date	Logged (ft)	Log start	Depth tag (ft)	Tag date	Fill since logged (ft)	Total fill (ft)
U-2ez-N10	1322.8	5/3/17	1301.5	5/15/17	1289.8	8/22/17	12	33
U-2ez-N20	1334.2	3/31/17	1306.7	4/12/17	1304.4	8/22/17	2	30
U-2ez-N40	1331.3	4/6/17	1251.9	4/17/17	1230.9	8/23/17	21	100
U-2ez-N80	1336.5	4/11/17	1320.6	4/18/17	1312.6	8/23/17	8	24
U-2ez-E10	1332.2	4/26/17	1294.0	5/9/17	1285.1	8/22/17	9	47
U-2ez-E20	1330.2	3/29/17	1325.0	5/8/17	1323.4	8/22/17	2	7
U-2ez-E40	1330.0	4/19/17	1315.5	5/10/17	1300.4	8/22/17	15	30
U-2ez-E80	1330.3	4/21/17	1318.0	5/9/17	1313.6	8/22/17	4	17
U-2ez-SW10	1322.5	5/1/17	1313.7	5/16/17	1307.3	8/22/17	6	15
U-2ez-SW20	1321.3	3/27/17	1319.4	4/11/17	1316.6	8/22/17	3	5
U-2ez-SW40	1334.0	3/16/17	1320.0	4/10/17	1316.2	8/22/17	4	18
U-2ez-SW80	1700.0	4/14/17	1690.8	4/19/17	1684.8	8/22/17	6	15
U-2ez					1297.5	8/22/17		

Table courtesy of NSTec Geology and Geophysics Team

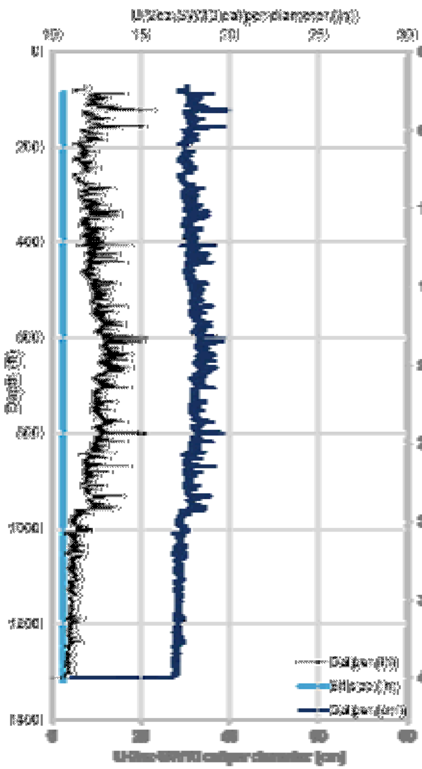
Hole Shapes (N Line)

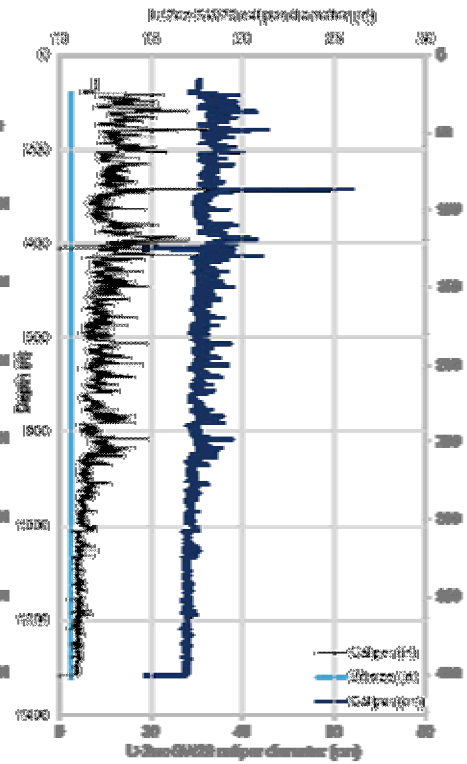


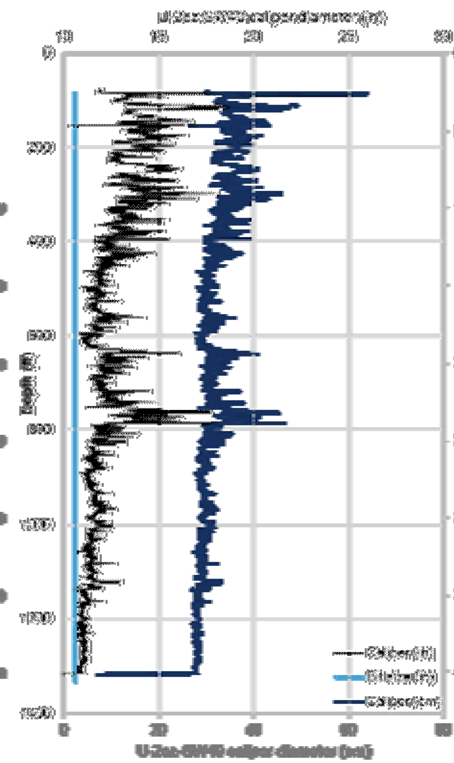
Hole Shapes (E Line)

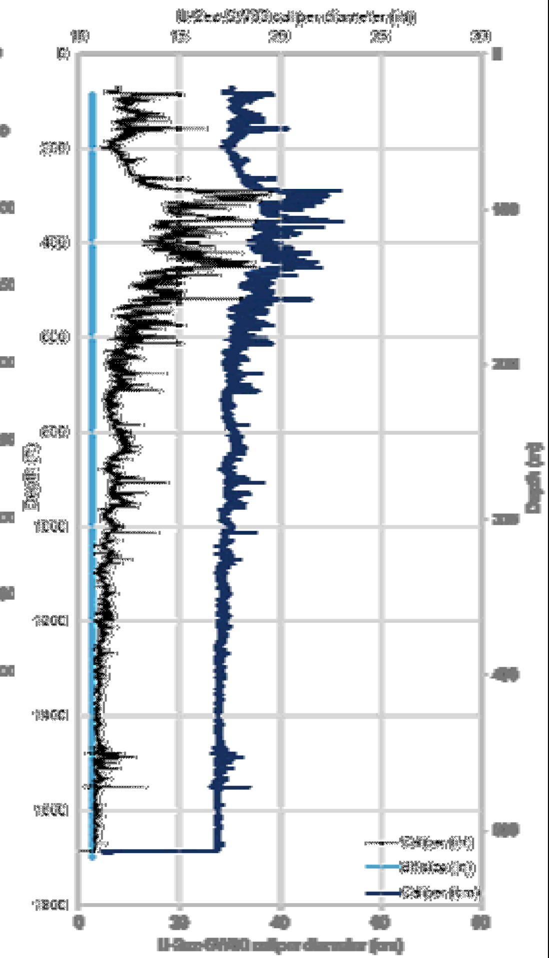


Hole Shapes (SW Line)



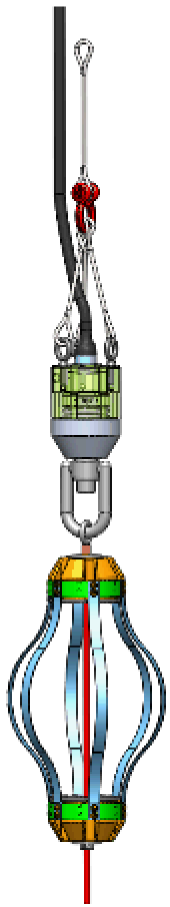




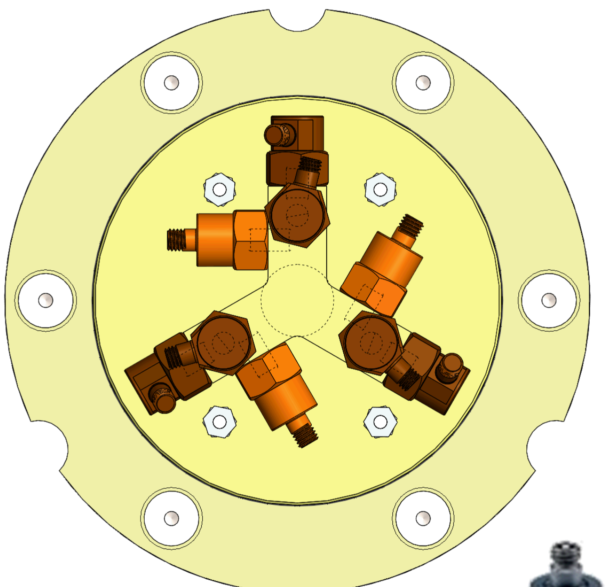


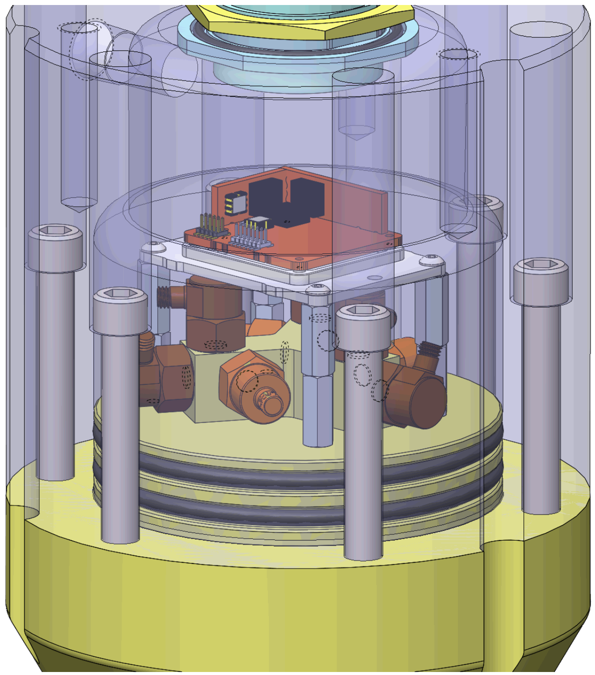
Installation Configuration

- Centralizers above and below module
- Centralizer rotates around cable

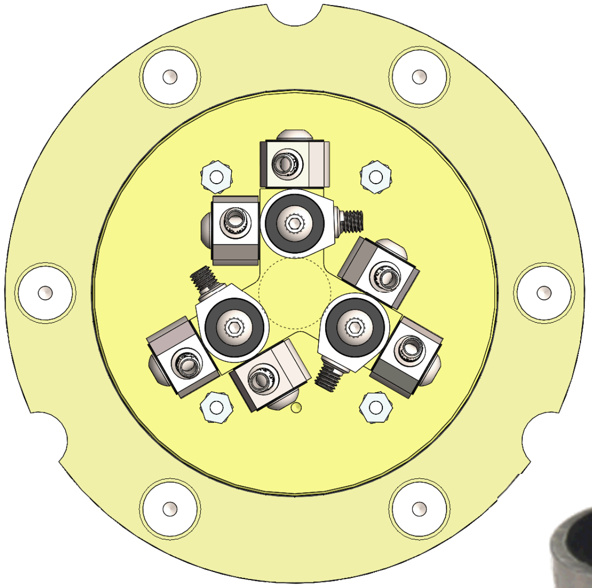


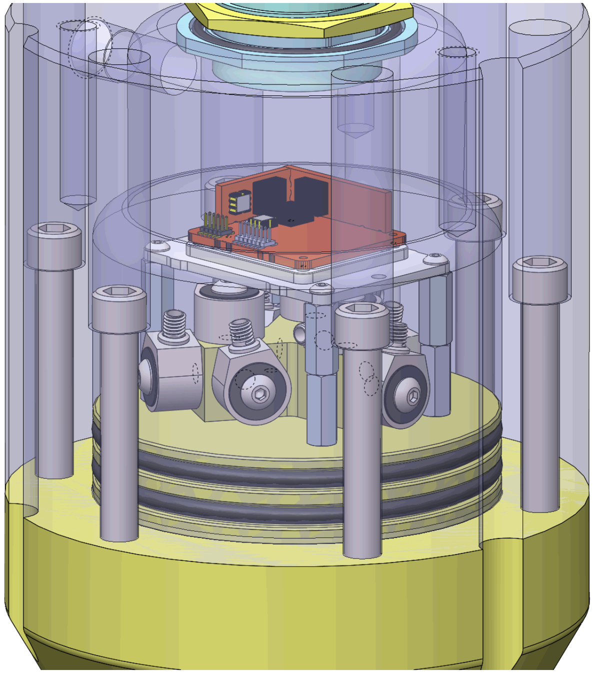
Config 1 (5g Meggitt 41A and 42A)



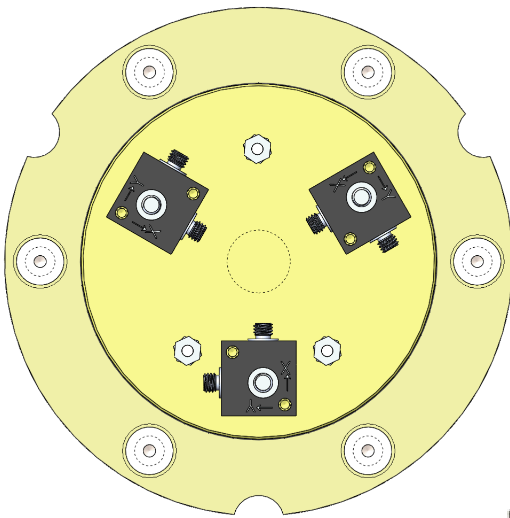


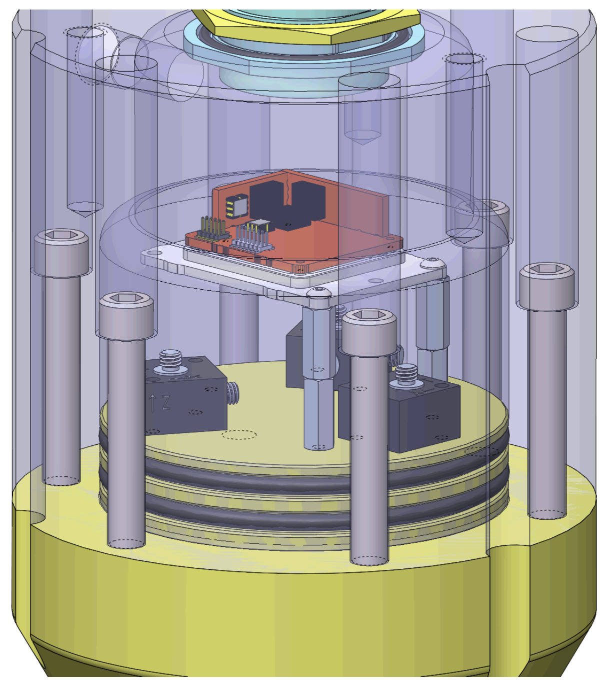
Config 2 (10g TE 7100A)



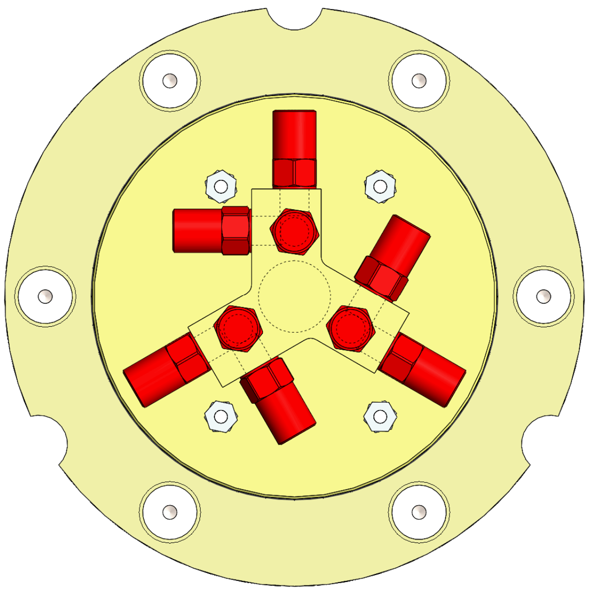


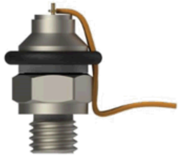
Config 3 (50g, 100g, 1kg, 5kg)

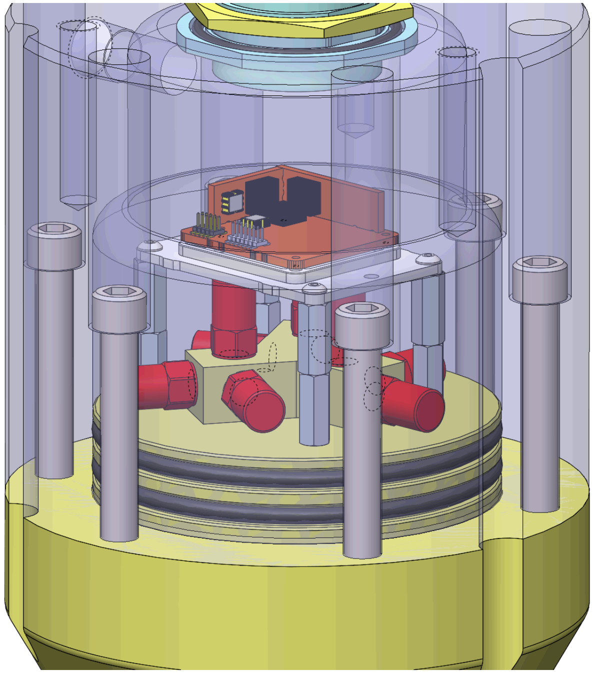




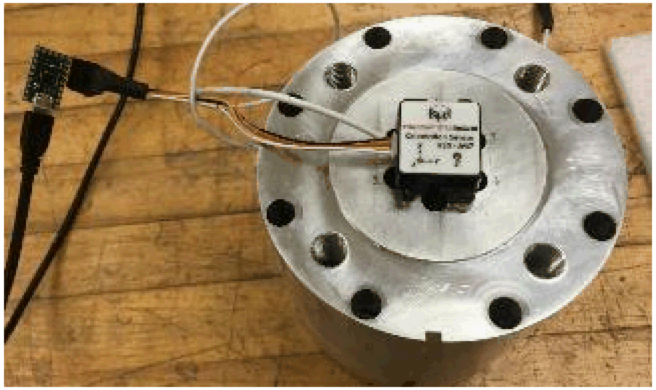
Config 4 (50kg)

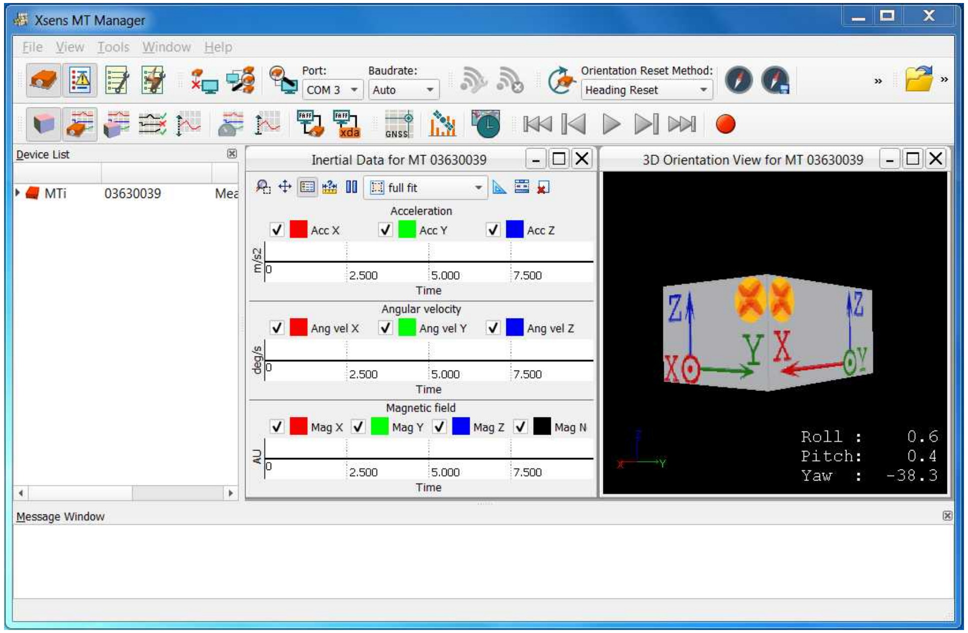






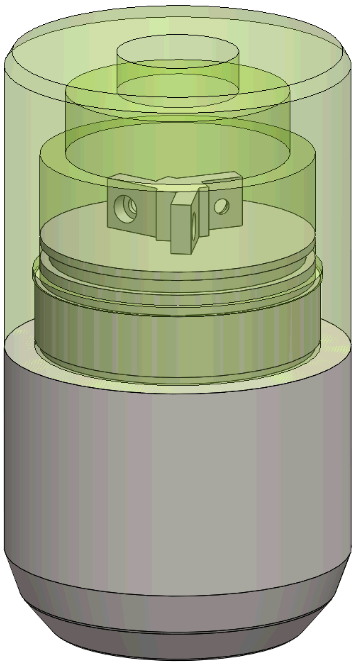
Downhole Orientation Measurement

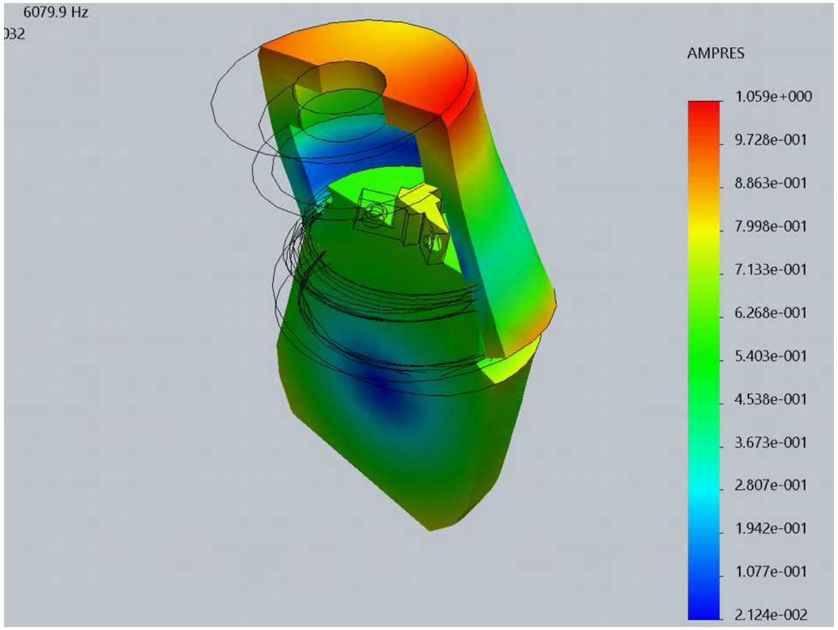




Modal Analysis

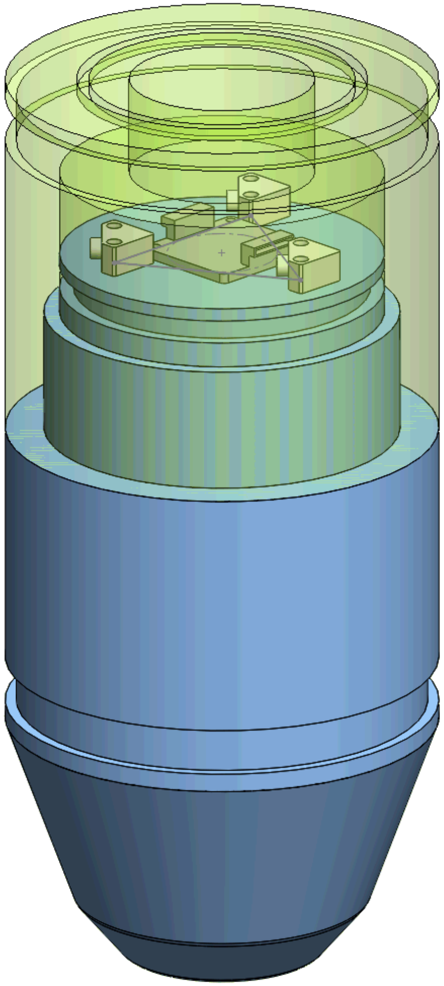
Simplified Module for Analysis





1st Mode of Vibration ~6100 Hz

Simplified Module Concept



- Aluminum 6061-T6
- Lowest Resonant Frequency: >6kHz
- 3 tri-axial accels per module or 9 uniaxial
- 1 AHRS
- Sealed 24 pin connectors

Encapsulant Fill Compound

3M

Scotch-Weld™

Epoxy Potting Compound/Adhesive

DP270 Clear and Black

Features

- Good Thermal Shock Resistance
- Meets UL 94 HB (File No. E61941)
- Long Worklife
- Excellent Electrical Properties
- Noncorrosive to Copper
- Negligible Exotherm

Electrical Cable

Specification Sheet

Lake Cable Part #: T2012SPOS

Description: 20AWG 12 pair 7 strand bare copper wire, PVC insulation, individually and overall shielded, with an overall PVC jacket. (UL) ITC or PLTC 105'C SUN RES FT-4 "ROHS"

1. Conductor

1.1. AWG Size & Stranding: 20AWG 7 Strands Class B
1.2. Material: Annealed Bare Copper
1.3. Conductor Count: 12 Pair

2. Insulation

2.1. Material: Polyvinylchloride
2.2. Wall Thickness: 0.018"
2.3. Color Code: Black & White numbered

3. Assembly

3.1. Pair Lay Length: 2.50" LHL (4.80 Tw/Ft) Nom.
3.2. Pair Drain wire: 22 AWG 7 Strand Tinned Copper
3.3. Pair Shield: FFE Aluminum Mylar – 100% Coverage
3.4. Pair Binder: Clear Mylar Tape – 100% coverage
3.5. Cable Lay Length: 8.50" LHL (1.41 Tw/Ft) Nom.
3.6. Cable Drain wire: 20 AWG 7 Strand Tinned Copper
3.7. Cable Shield: Aluminum Mylar Tape – 100% Coverage
3.8. Cable Binder: Clear Mylar Tape – 100% coverage

4. Jacket

4.1. Material: Polyvinylchloride
4.2. Wall Thickness: 0.060"
4.3. Diameter: 0.688"
4.4. Color: Natural
4.5. Ripcord: Yes
4.6. Weight: 262 Lbs/Mft

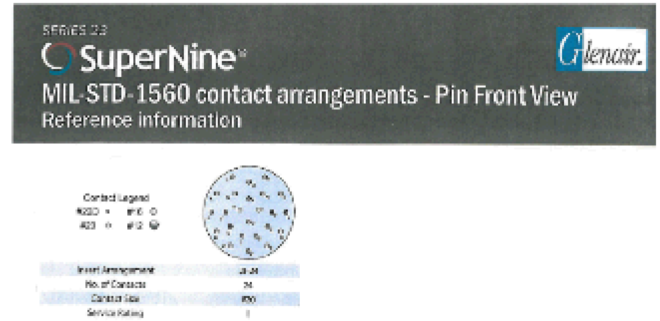
5. Markings

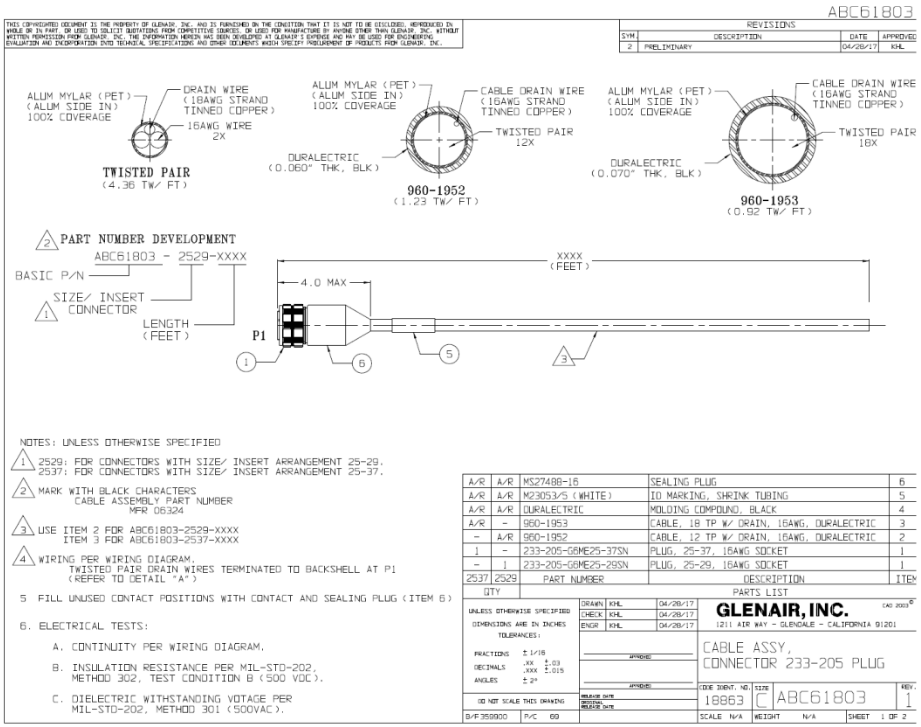
5.1. Type: Cable permanently identified via surface inkjet print
5.2. Legend: LAKE CABLE E171202 20AWG 12PR SPOS (UL) PLTC OR (UL) ITC OR (UL) CL3 105'C SUN RES FT-4 "ROHS"
5.3. Footage Markers: Yes

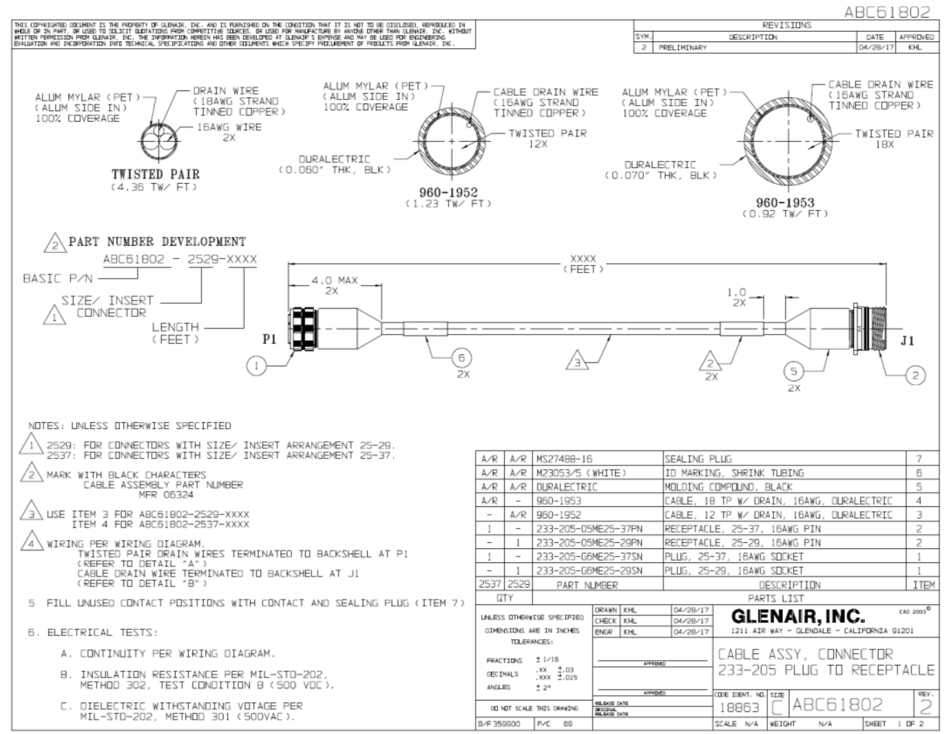
6. Standards

6.1. UL listed as type PLTC & CL3 per UL standard 13 and as type ITC per UL standard 2250
6.2. Cable is suitable for use in Class I Division II hazardous locations
6.3. Cable is UL approved for Sunlight Resistant Applications
6.4. Meets IEEE 1202 flame test
6.5. All materials used in the manufacture of this cable are RoHS compliant
6.6. Maximum Voltage: 300V
6.7. Made in the USA

Cable Assembly Drawings

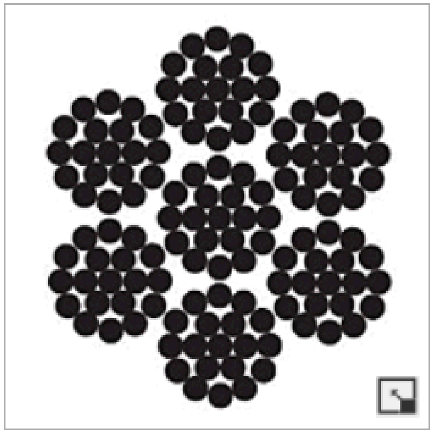






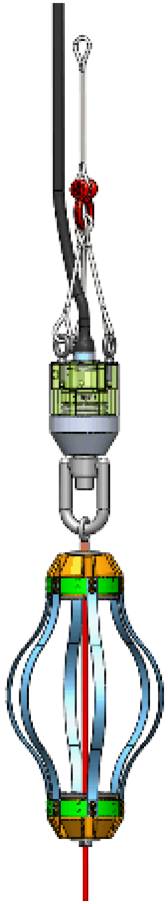
Structural Cable

Item # 38719GAC, 7x19 GAC



Adheres to Federal Specification RR-W-410, Type VI, Class 3

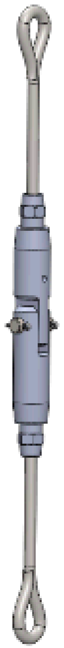
Available MIL-W-83420 type1 comp A

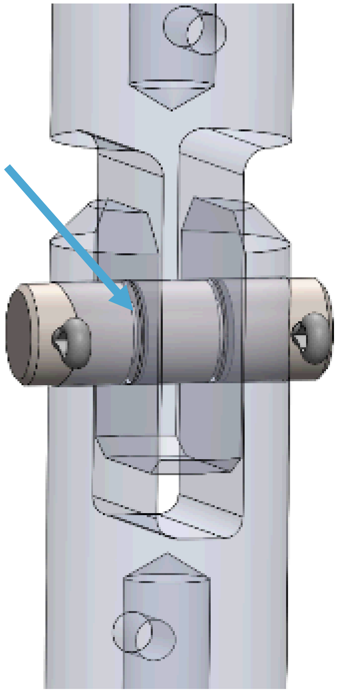


Specifications

Dia (in)	3/8
MBS (lbs) ?	14400
WT/1000FT (lbs)	243.0

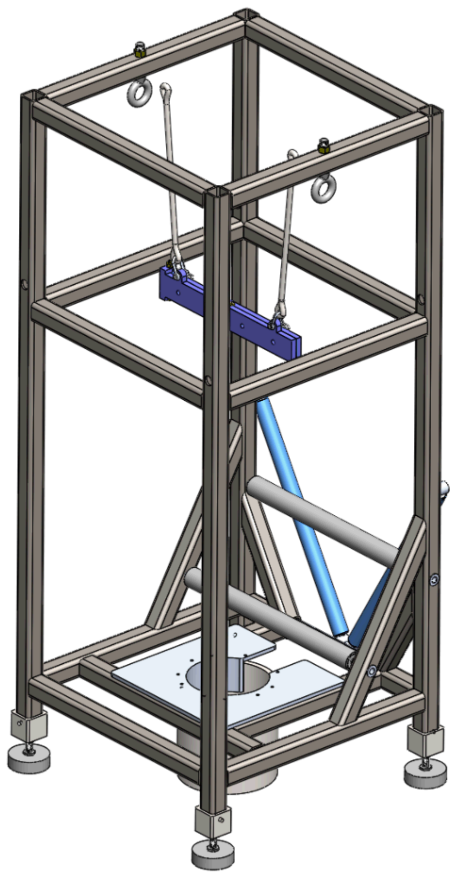
Break Away Assembly – Shear Pin

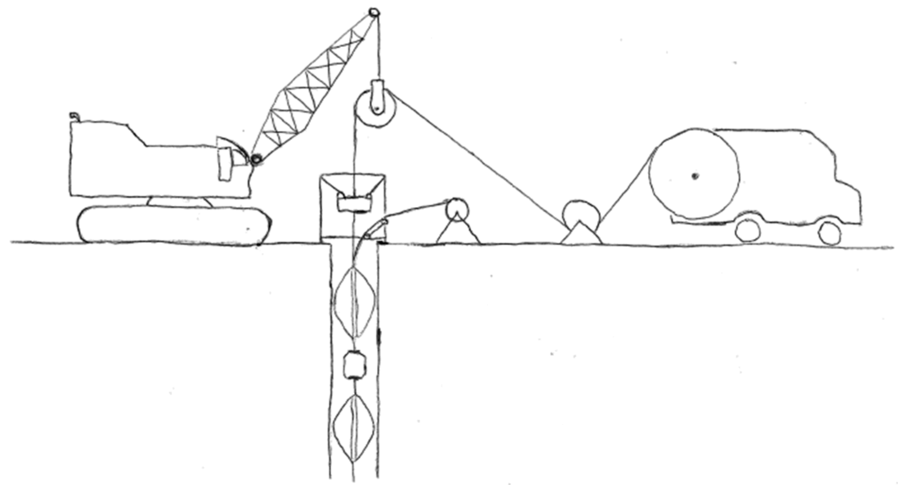


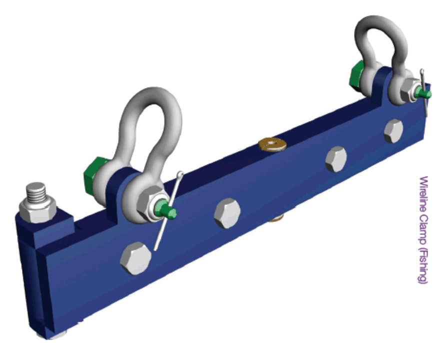


- Engineered Break Force
- Lanyard Break-Away electrical connectors attached to top assembly

Installation Configuration





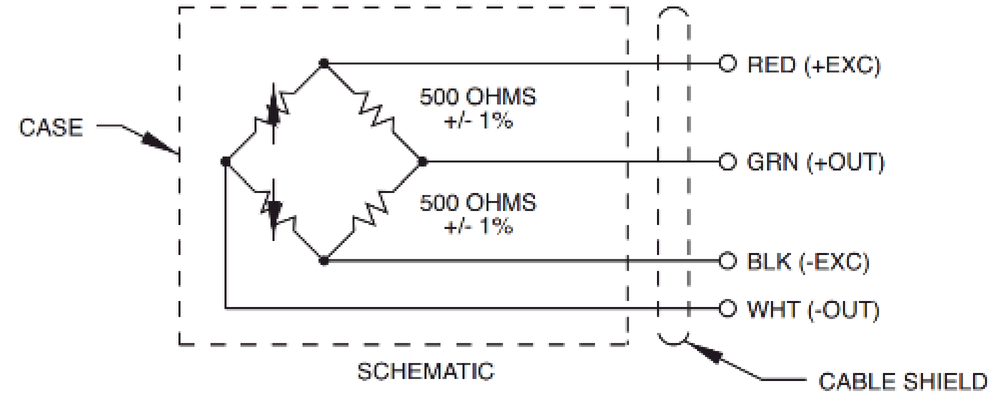


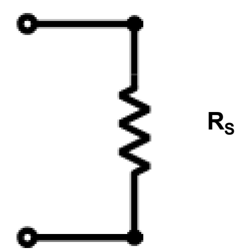
Accelerometers

- All accelerometers ranged a minimum of 3X maximum predicted acceleration
- Triaxial IEPE Accelerometers where possible. Uniaxial IEPE where necessary.
  - Industry standard is 4 pin connector (shared ground) which negates twisted pair wire configuration and causes ground loops
  - All accelerometers here have independent grounds and isolated mounting casing
- 3 triaxial accelerometers per module. 9 uniaxial accelerometers where necessary.
- Mounting pattern: Triaxial sets mounted 120 degrees apart on the same radius
- Z-axis oriented upward, X and Y orthogonal to Z
- Minimum 5,000g shock survival rating

Bridge Accelerometers (SPE Phase I)

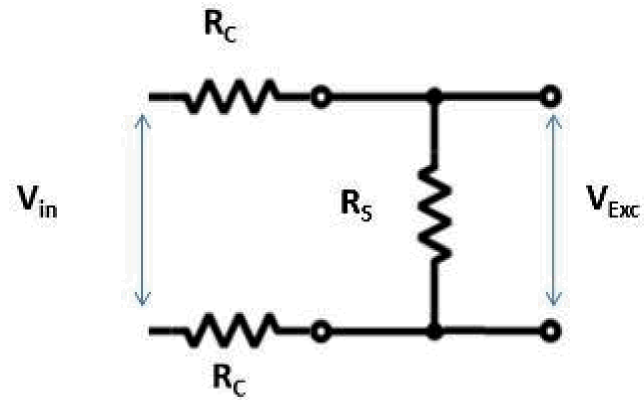
- Wheatstone architecture
- Piezoresistive sensing elements
- Thevenin Equivalent Circuit
- Sensitivity is dependent on excitation voltage
- High output impedance makes them susceptible to noise sources
- DC to kHz





4-wire vs. 6-wire

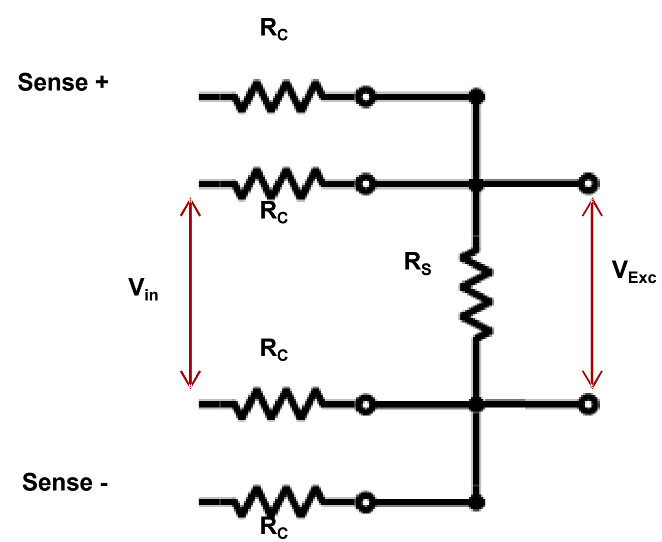
4-wire



$$\frac{V_{in}}{2 * R_C + R_S} = \frac{V_{Exc}}{R_S}$$

$$V_{Exc} = \frac{V_{in} R_S}{2R_C + R_S}$$

6-wire



IEPE Accelerometers

- Constant Current Source (2mA – 20mA)
- Low output impedance signal superimposed on DC power signal
- Only 2 wires required per axis
- Very robust over long cable length with low noise susceptibility
- ~1Hz – kHz
- Surface signal conditioners required for full bandwidth

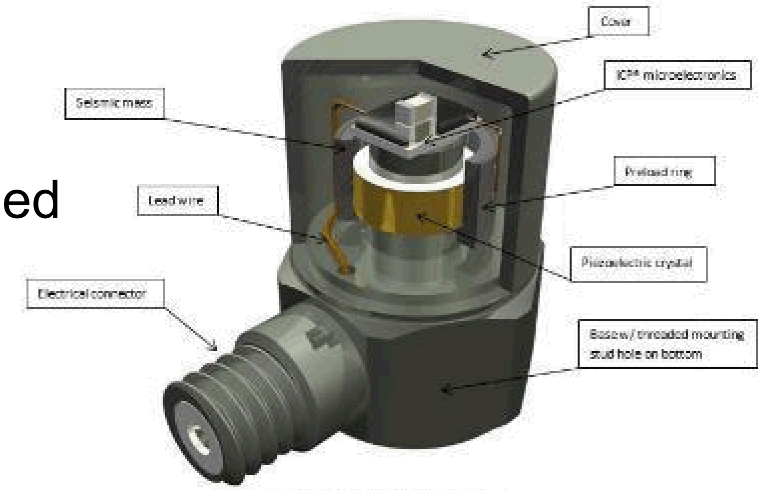
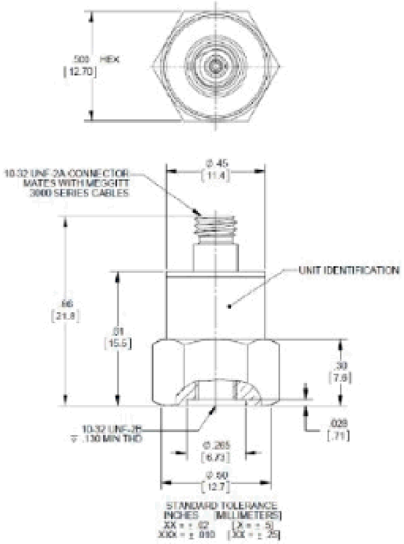


Figure 1. Typical ICP® Accelerometer

5g Accelerometer Selection

Isotron® accelerometer
Model 41A



Model 41A is a cost effective general purpose Isotron accelerometer designed for use in a variety of applications. 41A is a small hex shaped Isotron accelerometer with a 10-32 top mount connector. The unit is hermetically sealed against environmental contamination.

41A features an annular shear ceramic crystal which exhibits excellent output stability over time. The accelerometer incorporates an internal hybrid circuit with TEDS in a two-wire IEPE system which transmits its low impedance voltage output through the same cable that supplies the constant current power. Signal ground is electrically isolated from the outer case of the unit. Polarity inversion protection for the hybrid circuit is inherent in the circuit design.

Key features

- General purpose single axis Isotron® accelerometer
- 10-32 top connector
- Wide frequency bandwidth
- Hermetically sealed
- Lightweight
- Signal ground isolated from mounting surface
- IEEE P1451.4 TEDS capable

50g, 100g, 1kg, 5kg Accelerometer Selection

MODEL 7130A ACCELEROMETER

SPECIFICATIONS

- **Triaxial IEPE Accelerometer**
- **Wide Bandwidth to 9kHz**
- **Hermetically Sealed**
- **Annular Shear Mode**

The Model 7130A is a triaxial IEPE accelerometer available in ±50g to ±500g dynamic ranges. The accelerometer features three independent welded stainless steel assemblies incorporated into a hard anodized aluminum housing. The model 7130A incorporates a stable piezo-ceramic crystal in annular shear mode, installed with a compression ring that eliminates the usage of epoxies that can affect long term stability. The accelerometer has an operating range of -55°C to +125°C and a flat frequency response to 9kHz.

10g Accelerometer Selection

RoHS CE

MODEL 7100A ACCELEROMETER

SPECIFICATIONS

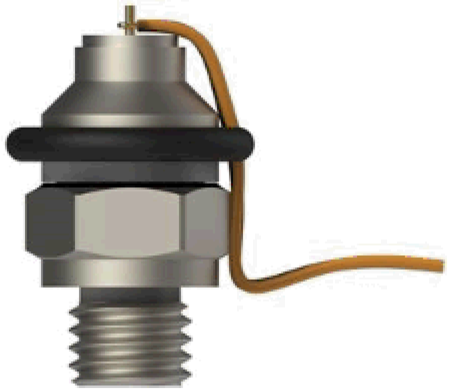
- **+150°C IEPE Accelerometer**
- **Wide Bandwidth to 15kHz**
- **Hermetically Sealed**
- **Through Hole Mount**

The Model 7100A is a high performance IEPE accelerometer with an operating temperature range of -55°C to +150°C. The accelerometer is available in ±50 to ±500g ranges and provides a flat frequency response up to 15kHz. The model 7100A is hermetically sealed and features the popular through hole mount installation for use with standard mounting screws.

High Shock Accelerometer Selection

MODEL 3086A2, SHOCK ACCELEROMETER

Model# 3086A2



FEATURES:

- 0.1 mV/g sensitivity
- 50,000g range
- 0.35 to 10,000 Hz frequency range (±10%)
- Axial mounted solder pins
- 1/4-28 stud mount
- 3.5 grams
- Titanium
- Hermetic
- Base isolated
- Lightweight
- High natural frequency of 100 kHz
- IEPE

APPLICATIONS:

- Drop testing
- Far field blast testing
- Pyrotechnic testing
- Shock testing

Accelerometer Selections

- DAG-1
  - 10m: TE 7130x (+/- 100g) IEPE
  - 20m: TE 7130x (+/- 50g) IEPE
  - 40m: TE 7100A (+/- 10g) IEPE
  - 80m: Meggit/Endevco 41A and 42A (+/- 5g) IEPE
- DAG-2
  - 10m: PCB 350D02 (+/- 50kg) ICP
  - 20m: TE 7130x (+/- 1kg) IEPE
  - 40m: TE 7130x (+/- 50g) IEPE
  - 80m: TE 7100A (+/- 10g) IEPE
- DAG-3
  - 10m: TE 7130x (+/- 5kg) IEPE
  - 20m: TE 7130x (+/- 50g) IEPE
  - 40m: TE 7100A (+/- 10g) IEPE
  - 80m: Meggit/Endevco 41A and 42A (+/- 5g) IEPE
- DAG-4
  - 10m: TE 7130x (+/- 5kg) IEPE
  - 20m: TE 7130x (+/- 50g) IEPE
  - 40m: TE 7100A (+/- 10g) IEPE
  - 80m: Meggit/Endevco 41A and 42A (+/- 5g) IEPE
- Deep Gauge
  - SW80: Meggit/Endevco 41A and 42A (+/- 5g) IEPE

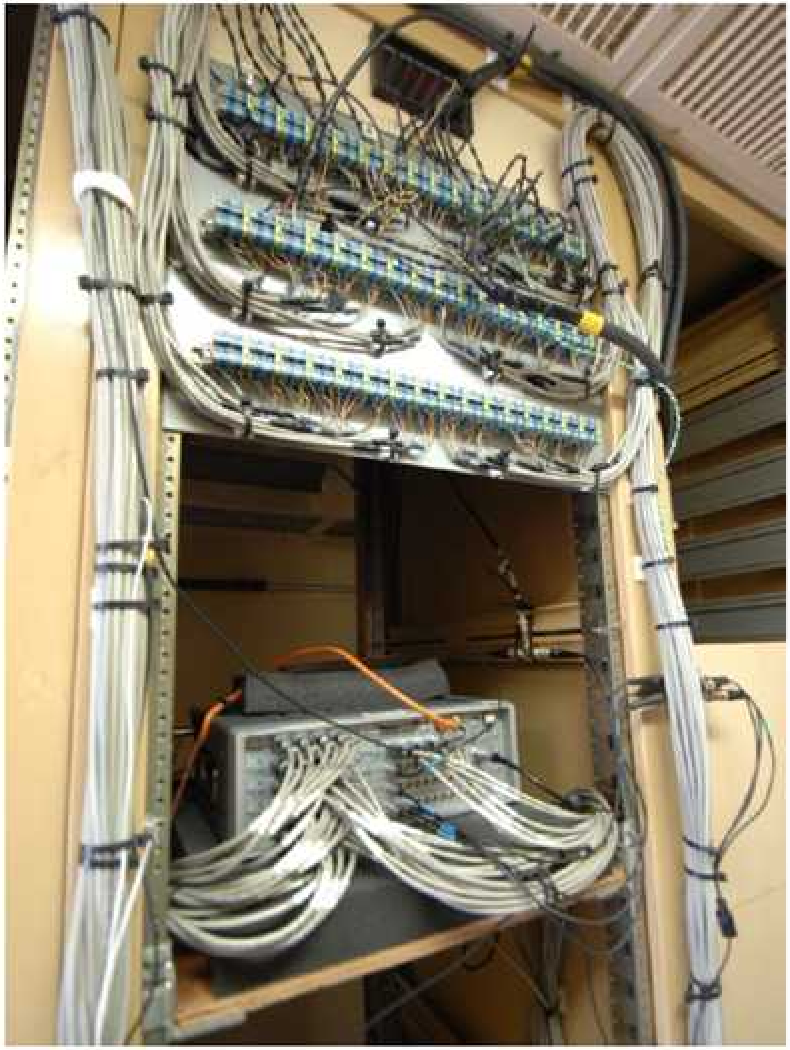


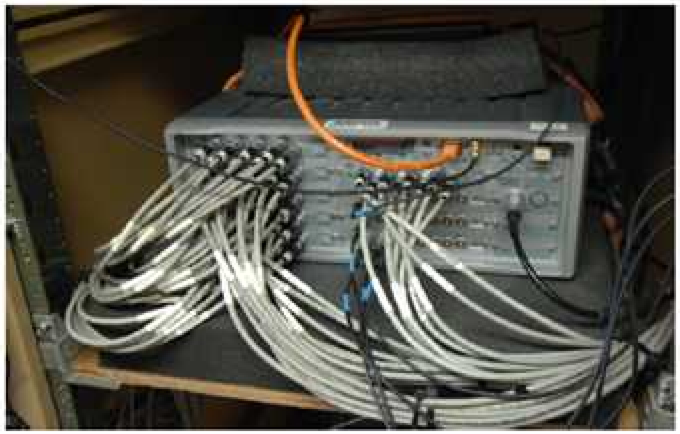
Accelerometer Specification Sheets

- 5g: http://pdf.directindustry.com/pdf/meggitt-sensing-systems-measurement-group/41a/5413-659294.html
- 10g: http://www.te.com/commerce/DocumentDelivery/DDEController?Action=showdoc&DocId=Data+Sheet%7F7100A_Accelerometer%7FA1%7Fpdf%7FEnglish%7FENG_DS_7100A_Accelerometer_A1.pdf%7FCAT-PPA0081
- 50g/100g/1kg/5kg: http://www.te.com/commerce/DocumentDelivery/DDEController?Action=showdoc&DocId=Data+Sheet%7F7130A_Accelerometer%7FA1%7Fpdf%7FEnglish%7FENG_DS_7130A_Accelerometer_A1.pdf%7FCAT-PPA0094
- 50kg:http://www.dytran.com/Model-3086A2-Shock-Accelerometer-P2352.aspx

LMS Digitizer

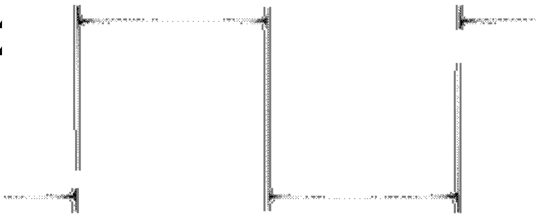
- LMS Scadas Recorder
- 51,200 Hz Sample Rate (19.5µs time resolution)
- 24-bit digitization
- 72-Channels
- Fiber optic connection to T&F trailer

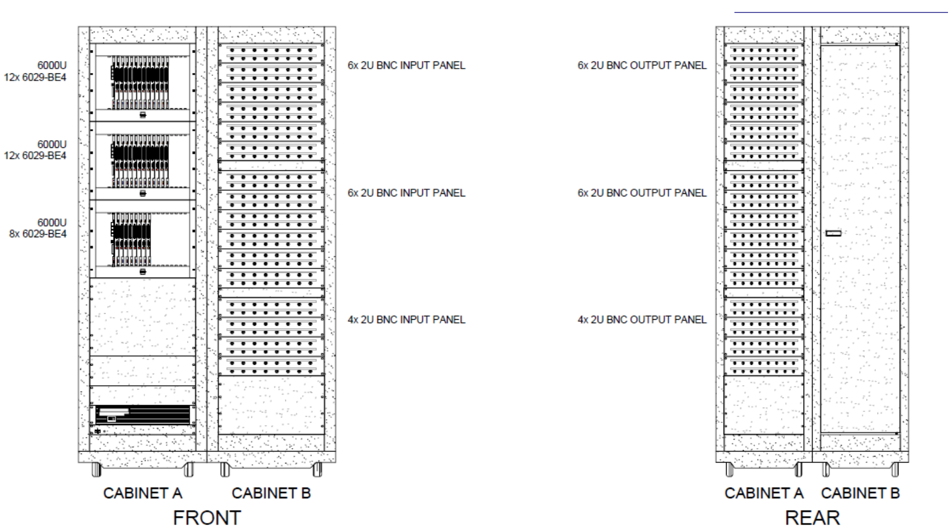


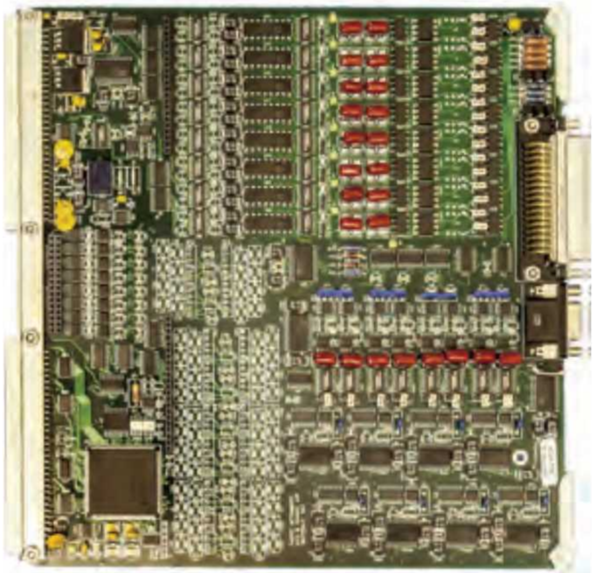


Digitizer Considerations and Options

- Bandwidth issues with LMS VB8-II cards (LMS
- Gibbs phenomenon from Sigma-Delta ADCs
- IEPE signal conditioners required regardless.
- Option for on-board digitizing signal conditioner (SAR)
- Isolated ground signal conditioners
- Analog output to digitize with LMS







LMS Channel Economics

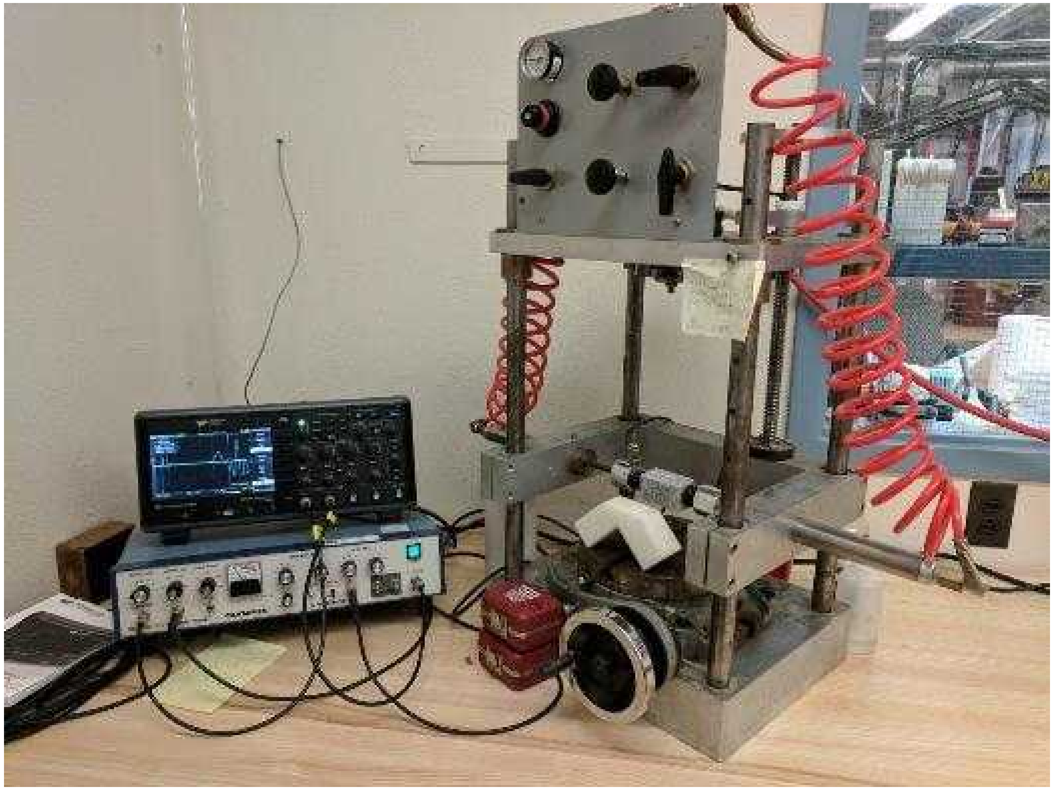
- 58 modules total (36 modules in stage 1, 46 in stage 2)
- 3 triaxial gauges per module = 9 possible channels per module
- Maximum possible channel count (stage 2): 414
- 71 channels can be recorded per LMS.
  - 256 channels with spec'd signal conditioner/SAR digitizer
- 108 channels per experiment depth + 81 off depth (green pods) = 189
- Recording one triax from all modules (stage 2): 138
- Recording all from DAG1 and DAG2: 216 + deep gauge = 217
- Note: Some LMS channels are requested for EM measurements

Grout Property Measurements

- Sandia rock mechanics lab P-wave and S-wave velocity measurements

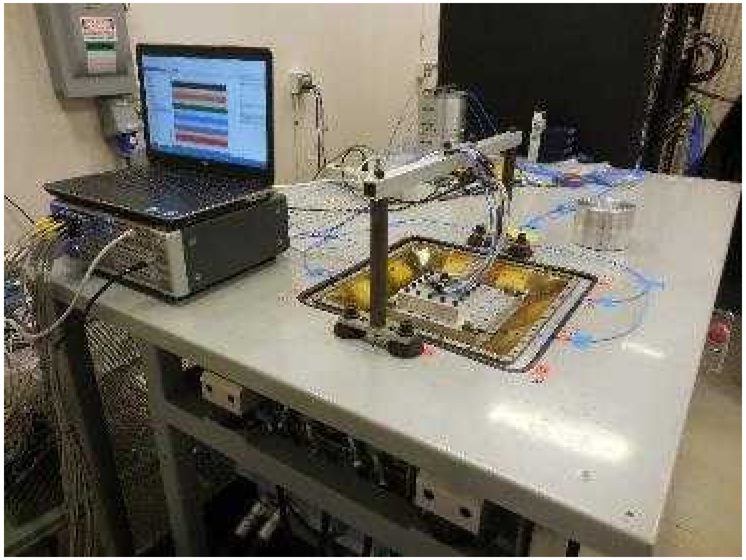
- Portland cement, fly ash, additives velocity: ~2370m/s
- Cement density: ~1.59 g/cc

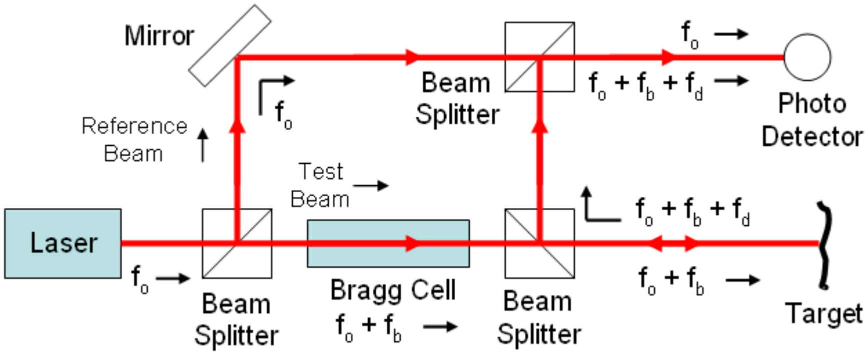
- U-2ez average velocity: ~1700m/s
- U-2ez average density: ~2.0 g/cc



Triaxial Shake Table Testing

- Triaxial vibration platform
- 3 dimensional Laser-Doppler Vibrometer (LDV)
- Integrated module acceleration vs laser displacement and velocity data





BH Geophones for Consideration

Micromate® Borehole Triaxial Geophone

*Instructions sheets are available in additional languages at www.Instantel.com

The Borehole Triaxial Geophone is lowered into a borehole to measure vertical, transverse and longitudinal ground vibrations.

Tools and Materials Required

- An ISEE or DIN Micromate monitoring unit calibrated with a Borehole Triaxial Geophone
- Micromate extension cables, as required
- Instantel® PC software , as required
- Steel cable to position the geophone into the borehole (length as required)

Specifications

Part No.	Standard Cable Length	Maximum Cable Length
721A2401	30 m (100 ft.)	1000 m (3280 ft.)
721A2402	75 m (250 ft.)	1000 m (3280 ft.)

Frequency Range

For Micromates/Borehole Geophones calibrated to the ISEE 2011 standard	For Micromates/Borehole Geophones calibrated to the DIN 45669-1 standard
2 to 250 Hz	1 to 315 Hz

Readiness

- Technical
  - Design (Complete)
  - Hardware/Assembly (In progress. December completion)
  - Qualification/Demonstration (August-December)
- Procedures/Checklists
  - Module Configuration Management (SN, PN tracking)
  - Assembly Checklist (Pin configuration verification, torque spec, power test, flip test)
  - Two person installation verification on structural cable
  - Keyed electrical connectors
  - Test cart for module verification at the borehole
- Authorizations
  - SNL Work Package Preparation (October)
  - NNSS Work Package Preparation (October)
- Training
  - All personnel will have required training

Installation needs from the NNSS

- Wireline truck (5,000 ft structural cable spool, capability to replace spool)
- Crane-mounted sheave for wireline (supplementary sheave equipment)
- Aluminum or Stainless Steel tremie pipe if possible
- Grouting equipment and expertise (4 or 5 7-yard trucks to fill one hole, staged grouting preferred i.e. one truck per day per hole)
- Cable spool structure for electrical cable feed (6 large spools)
- 20mA IEPE signal conditioners (1 per accelerometer channel)
- Digitizer
- 19” rack mount space in instrumentation trailer
- Fiber link to instrumentation trailer from operations trailer

Risk

- Sensor/System Risks
  - Hole collapse during installation or between DAG-2 and DAG-3.
  - Accelerometer string wrapping around tremie pipe could cause issues with pipe removal and grouting
  - Excessive cable abrasion could damage signal integrity
  - Borehole quality may create installation challenges
- Weather Risks
  - Lightning damage to digitizer, signal conditioners, or accelerometers
  - All exposed cables are rated for direct burial and direct sunlight
- Risks to participation
  - Digitizer or signal conditioner failures

Operations

- Access needed before shots
- Location of personnel during shots
  - Borehole Accel personnel will be at the control trailer monitoring equipment through the fiber link.
- Timeline of Fielding Activities
  - Two-Staged installation. Stage one will occur before DAG-1 and stage two will occur after DAG-2. Stage 1 is 4 weeks. Stage 2 is 1 week.
- Fielding Team (Experience in NNSS execution?)
  - Zack Cashion, Dennis King, Adam Foris, Sasha Egan, Jiann Su
  - Team is experienced in sub-surface field installations including NNSS.
- Resources needed from Execution Team
  - 110v AC Power
  - 2-way COM
  - Digitizer Triggers (one for each digitizer)
- Frequencies provided to NNSS
  - N/A

Operations (2/2)

- ES&H Concerns
  - Standard operational hazards apply (overhead equipment, heavy machinery, power tools, pinches, slips, trips, falls, wildlife, weather, dehydration, etc.)
- Go/No Go Criteria
  - Each module will be tested before going in the hole and just before grouting
  - If a module is determined broken before grouting, the installation will be pulled and started over
- Plans for changing sensor/systems after experiment for the next DAG experiment
  - Between DAG-2 and DAG-3, the borehole installations at 10m and 20m will be released at 200m depth and the string removed. A new installation for DAG-3 and DAG-4 will be put in place.

DAG Deliverables

- Required deliverable
  - Raw data from all recorded borehole accelerometers
  - Cropped records of accelerations from t-minus 100ms to t-plus 2sec
- Timeline for delivery
  - Raw data delivered experiment day
  - Cropped data delivered <1 week following each experiment day
- Quality analysis
  - Borehole accelerometer team and near-field committee will work collaboratively to assess data quality
- Written documentation
  - As-installed and build reports

Lessons Learned from Past Experiments

- IEPE accelerometers instead of bridge accelerometers to decrease the output impedance, noise susceptibility, and cable count
- Triaxial accelerometers where possible
- Direct mounting of accelerometers to module body rather than secondary triaxial block structure.
- Individually shielded, twisted pair cables to prevent signal contamination from adjacent signals, triboelectric effects, ground loops
- Knurled module surfaces to enhance grout coupling
- SAR or FLASH ADCs if possible to avoid Gibb's phenomenon

Next Steps

- Describe next steps
  - Meetings at the NNSS
  - Complete Sandia and NNSS Work Packages
  - Procurement completion
  - Module manufacturing
  - Benchtop assembly
  - Shake table testing
  - Verification and Validation
  - Field Installation and testing
  - Dry runs