LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type	**LIGO-T080317-00-H**	2008/11/03

Impact of Seismic Survey using Explosive Charges on the LIGO Livingston Interferometer

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Distribution of this draft:
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Processed with LaTeX on 2008/11/03

1 Introduction

Yuma Exploration and Production Company Inc. (www.yumaexploration.com) is planning a seismic survey covering 160 square miles (414 square kilometers) in Livingston Parish. The survey area begins east of the Livingston site and continues to the west. This is a 3-D survey employing explosive charges at depths of 40 to 100 feet (12 to 31 m). Their plan is for a source density of 58 sources per square mile detected with 68 instrument stations per square mile. Nominally this implies a distance of approximately 300 feet (100 m) between explosion sites. To deal with areas that are hard to instrument or drill and to avoid structures or water wells they can "offset" their pattern or sources and receivers. They normally stay at least 400 feet (122 m) from buildings and wells, and in preliminary discussions have indicated that staying 800 feet (244 m) from the LIGO central and end stations should be possible. Figure 1 shows the survey map for the area around the Observatory.

YUMA employs several subcontractors to acquire necessary permits (Exploration Land Services), to evaluate the survey effects on structures and wells (Urban Seismic Specialists), to perform the drilling and shoot the explosives (CGGVeritas). Urban Seismic Specialists try to ensure that the maximum ground velocity at 400 feet from the shot is 0.35 in/s (8.9e-3 m/s) although in practice they say that they are usually an order of magnitude below this).

Initially the survey will deploy drilling buggies to place the charges. These are rugged all-terrain vehicles which can easily travel through light forest (where the tree boles are 3 in in thickness or less). The actual shots are expected to be fired in March or April of 2009. Typically they can survey 70 square miles per month, so they expect to blast for 2.5 months. Blasting within 2 miles of any corner station should last from 2 to 4 weeks. This is a daytime activity only.

Commissioning activities during the daytime will be impaired by the extra seismic noise, especially when the survey team is in the immediate vicinity of the lab. What follows is a preliminary look at some test explosions with an eye to judging their impact on the detector from both an operational and safety viewpoint.

2 Test Blasts

On October 28 2008 CGGVeritas conducted 23 test explosions at a location 4.5 km from the LLO corner station. We attempted to monitor the explosions in the field using a Streckeisen STS-2 seismometer and two L4-C geophones, one oriented vertically and one horizontally. These instruments were set up 15 m from the closest sources and about 125 m from the furthest. In practice this proved to be far too close and the instruments saturated for many of the blasts. The STS-2 data was not useable and that instrument was locked down to prevent it from being damaged. Some of the blasts saturated our on-site STS-2 channels at the corner and end stations. We were however able to get good data from several of the blasts locally, and from all of the blasts using the Guralp seismometers at the corner and end stations. We have asked the monitors from Urban Seismic Specialists if we can have access to their data and are hopeful that this will be forthcoming. This would give us information up to 1000 feet (305 m) from the site of the blasts.

Figure 2 shows the blast area location relative to the LIGO site, Figure 3 shows a close up of the blast area. All the blasts occurred in a 400'x75' rectangle and used either Geoprime or Geoprime dBX as the explosive charge (Figures 4,5). The layout of the explosions is shown in Figure 6. The explosive charges varied in size from 2.2 lbs to 11 lbs.

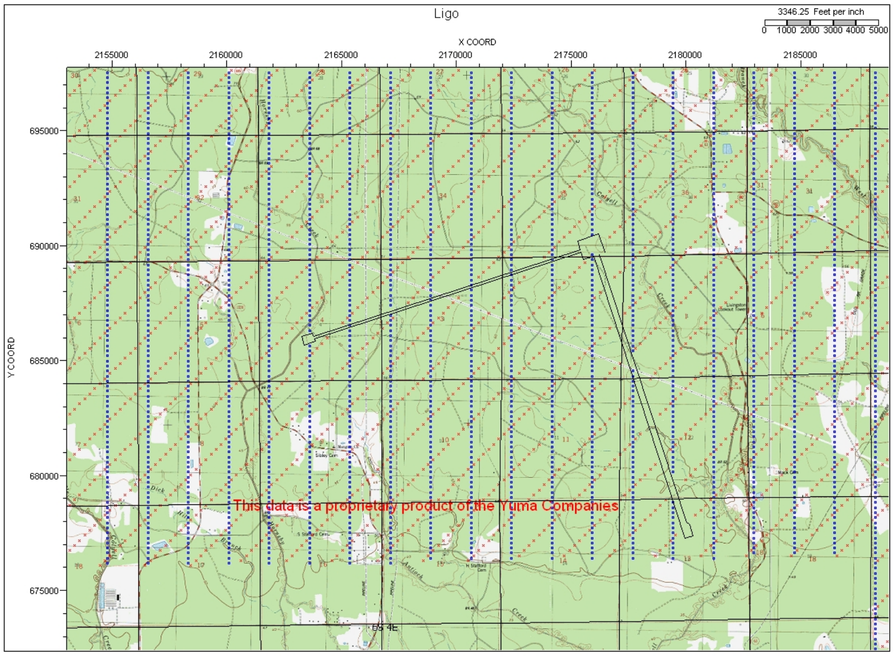
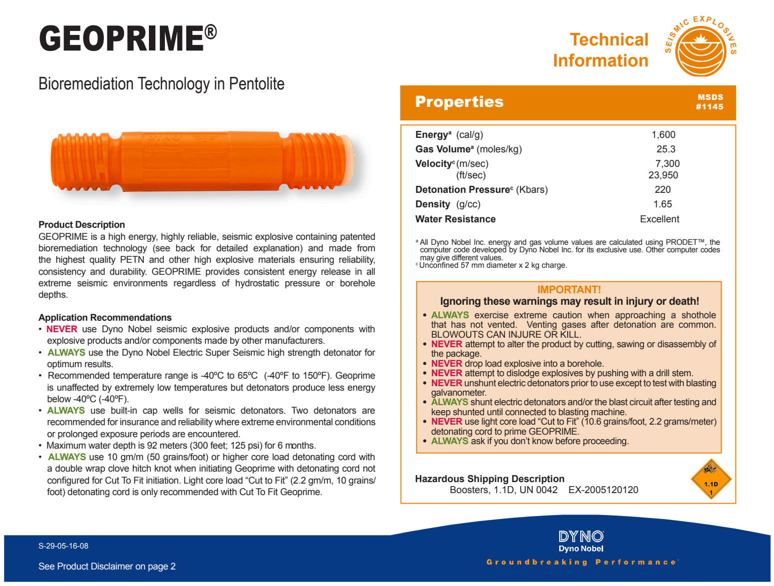


Figure 1: YUMA Survey Map. Detail of area near Livingston Observatory.

Figure 2: Map of Blast Site with distances to LIGO corner and end stations.

Figure 3: Detail of Blast Site. LIGO's field instruments were set up at the yellow placemark. The blasts were in the shaded in rectangle which was approximately 400'x75' in size.



GEOPRIME®

Bioremediation Technology in Pentolite

Product Description
GEOPRIME is a high energy, highly reliable, seismic explosive containing patented bioremediation technology (see back for detailed explanation) and made from the highest quality PETN and other high explosive materials ensuring reliability, consistency and durability. GEOPRIME provides consistent energy release in all extreme seismic environments regardless of hydrostatic pressure or borehole depths.

Application Recommendations
- NEVER use Dyno Nobel seismic explosive products and/or components with explosive products and/or components made by other manufacturers.
- ALWAYS use the Dyno Nobel Electric Super Seismic high strength detonator for optimum results.
- Recommended temperature range is -40ºC to 65ºC (-40ºF to 150ºF). Geoprime is unaffected by extremely low temperatures but detonators produce less energy below -40ºC (-40ºF).
- ALWAYS use built-in cap wells for seismic detonators. Two detonators are recommended for insurance and reliability where extreme environmental conditions or prolonged exposure periods are encountered.
- Maximum water depth is 92 meters (300 feet; 125 psi) for 6 months.
- ALWAYS use 10 gm/m (50 grains/foot) or higher core load detonating cord with a double wrap clove hitch knot when initiating Geoprime with detonating cord not configured for Cut To Fit initiation. Light core load "Cut to Fit" (2.2 gm/m, 10 grains/foot) detonating cord is only recommended with Cut To Fit Geoprime.

Technical Information

SEISMIC EXPLOSIVES

Properties MSDS #1145

Energy[a] (cal/g)	1,600
Gas Volume[a] (moles/kg)	25.3
Velocity[c] (m/sec)	7,300
(ft/sec)	23,950
Detonation Pressure[c] (Kbars)	220
Density (g/cc)	1.65
Water Resistance	Excellent

[a] All Dyno Nobel Inc. energy and gas volume values are calculated using PRODET™, the computer code developed by Dyno Nobel Inc. for its exclusive use. Other computer codes may give different values.
[c] Unconfined 57 mm diameter x 2 kg charge.

IMPORTANT!
Ignoring these warnings may result in injury or death!
- ALWAYS exercise extreme caution when approaching a shothole that has not vented. Venting gases after detonation are common. BLOWOUTS CAN INJURE OR KILL.
- NEVER attempt to alter the product by cutting, sawing or disassembly of the package.
- NEVER drop load explosive into a borehole.
- NEVER attempt to dislodge explosives by pushing with a drill stem.
- NEVER unshunt electric detonators prior to use except to test with blasting galvanometer.
- ALWAYS shunt electric detonators and/or the blast circuit after testing and keep shunted until connected to blasting machine.
- NEVER use light core load "Cut to Fit" (10.6 grains/foot, 2.2 grams/meter) detonating cord to prime GEOPRIME.
- ALWAYS ask if you don't know before proceeding.

Hazardous Shipping Description
Boosters, 1.1D, UN 0042 EX-2005120120

1.1D
1

S-29-05-16-08

See Product Disclaimer on page 2

DYNO
Dyno Nobel
Groundbreaking Performance

Figure 4: GEOPRIME explosive was used in 10 explosions

GEOPRIME® dBX™

High Performance Pentolite
Premium Seismic Energy Source

Product Description
GEOPRIME dBX is a high energy, high performance pentolite seismic explosive researched and engineered to increase elastic waves through improved coupling between the explosive energy and the earth. In a new approach to explosives application in geophysical exploration, GEOPRIME dBX offers high detonation velocity and superior low post-detonation gas production. GEOPRIME dBX produces improved seismic energy across the usable bandwidth for superior final stack data as well as improved signal-to-noise ratios. Designed by geophysicists and Dyno Nobel explosives engineers, GEOPRIME dBX is the next generation of seismic explosives.

Application Recommendations
- **NEVER** use Dyno Nobel seismic explosive products and/or components with explosive products and/or components made by other manufacturers.
- **ALWAYS** use Dyno Nobel's DiPED or Electric Super Seismic high strength detonator for optimum results.
- Recommended temperature range is -40º C to 65º C (-40º F to 150º F).GEOPRIME dBX is unaffected by extremely low temperatures but detonators produce less energy below -40º C (-40º F).
- **ALWAYS** use built-in cap wells for seismic detonators. Two detonators are recommended to minimize environmental issues with abandoned charges.
- **ALWAYS** use two Electric Super Seismic or DiPED Super Seismic detonators. A broken wire is the primary cause of abandoned seismic charges so protect your investment, increase performance and minimize liability. Require all personnel who handle or come into contact with explosive materials to be fully trained in the proper storage, handling and use of explosive products.
- GEOPRIME dBX maximum water depth is limited by the initiation system used.

Technical Information

SEISMIC EXPLOSIVES

Properties

MSDS #1145

Energy[a] (cal/g)	2,100
Gas Volume[a] (moles/kg)	16.0
Velocity[c] (m/sec)	7,400
(ft/sec)	24,250
Detonation Pressure[c] (Kbars)	236
Density (g/cc)	1.76
Water Resistance	Excellent

[a] All Dyno Nobel Inc. energy and gas volume values are calculated using PRODET™, the computer code developed by Dyno Nobel Inc. for its exclusive use. Other computer codes may give different values.
[c] Unconfined 57 mm diameter x 2 kg charge.

IMPORTANT!
Ignoring these warnings may result in injury or death!
- **ALWAYS** exercise extreme caution when approaching a shothole that has not vented. Venting gases after detonation are common. BLOWOUTS CAN INJURE OR KILL.
- **NEVER** attempt to alter the product by cutting, sawing or disassembly of the package.
- **NEVER** drop load explosive into a borehole.
- **NEVER** attempt to dislodge explosives by pushing with a drill stem.
- **NEVER** unshunt electric detonators prior to use except to test with blasting galvanometer.
- **ALWAYS** shunt electric detonators and/or the blast circuit after testing and keep shunted until connected to blasting machine.
- **NEVER** use Geoseis Cut-to-Fit (2 grams/meter; 10 grains/foot) detonating cord to prime GEOPRIME dBX.
- **ALWAYS** ask if you don't know before proceeding.

1.1D
1

Hazardous Shipping Description
Boosters, 1.1D, UN 0042

S-26-05-23-08

See Product Disclaimer on page 2

DYNO
Dyno Nobel
Groundbreaking Performance™

Figure 5: GEOPRIME_dbX explosive was used in 13 explosions

LIVINGSTON TEST

HOLE PATTERN, CHARGE SIZE AND HOLE DEPTH
(DBX AND GEOPRIME)

504103 11 X 60' DBX 25FT.
50FT.
504104 11 X 80' DBX
50FT.
504105 11 X 100' DBX
50FT.
505101 11 X 60' GP
50FT.
505102 11 X 80' GP
50FT.
505103 11 X 100' GP

503105 7.7 X 60' DBX 25FT.
50FT.
504101 7.7 X 80' DBX
50FT.
504102 7.7 X 100' DBX

502104 5.5 X 60' DBX 25FT.
50FT.
502105 5.5 X 80' DBX
50FT.
503101 5.5 X 100' DBX
50FT.
503102 5.5 X 60' GP
50FT.
503103 5.5 X 80' GP
50FT.
503104 5.5 X 100' GP

501101 2.2 X 40' DBX
50FT.
501102 2.2 X 60' DBX
50FT.
501103 2.2 X 80' DBX
50FT.
501104 2.2 X 100' DBX
50FT.
501105 2.2 X 40' GP
50FT.
502101 2.2 X 60' GP
50FT.
502102 2.2 X 80' GP
50FT.
502103 2.2 X 100' GP

Figure 6: Layout of the test blasts. Shot 502103 was 50' due north of our measuring equipment and was the closest explosion to us.

3 Blast 21, 505101

Plots for the other 23 test shots can be found at the end of this document. Here we present a detailed look at the blast which showed up strongly at the site. This blast was from 11 lbs of Geoprime at a depth of 60 feet.

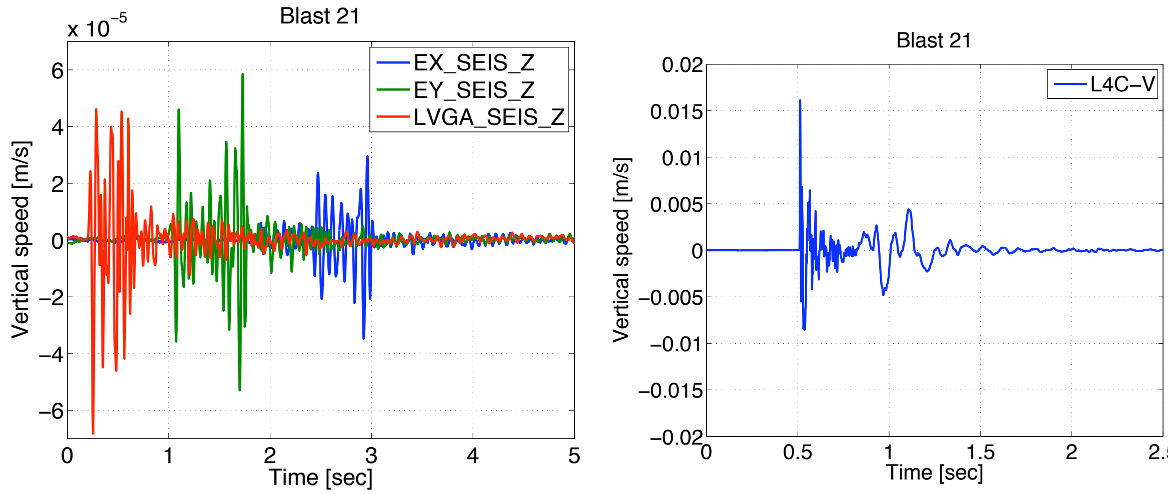


Figure 7: a) Velocity in the Z direction as seen by the on-site Guralp Seismometers. b)Velocity in the Z direction seen at the blast site from the vertical L4-C geophone.

Figure 7(a) shows the signal seen by the Guralp seismometers at the Livingston site. The peak velocity seen at the corner station is 7e-5 m/s. For a surface wave we expect the amplitude to fall off as $1/\sqrt{\mathrm{R}}$ whereas for a bulk wave we expect the behavior to be $1/\mathrm{R}$. Here the amplitude seems to fall off to 3.5e-5 m/s at the X end station, consistent with the latter. Figure 7(b) shows the signal seen locally with an L4-C geophone. The instrument was located approximately 261 feet (79 m) from the blast site and measures a peak velocity of 1.6e-2 m/s. If the amplitude is falling as $1/\mathrm{R}$ then we would expect a peak velocity at the corner station of 2.8e-4 m/s, where we have taken a simple ratio of the distances. The fact that we see a value lower than this implies that a simple model will not work. The blast location measurement is from the near-field and likely contains a mixture of unresolved waveforms.

Finally we note that the speed of the seismic wave seen by the Guralp seismometers is slightly less than 2 km/s. This is characteristic of a surface wave, although as we note above the decay of the peak amplitude is not.

The survey crew did note that they had hit sand for several of their hole depths. We don't yet know which holes had charges in sand and which had charges in regular clay. This may allow us to extract some simple scaling laws in the future.

It is probably good news for us that the signals detected by the Guralps seem to have characteristic frequencies above 10 Hz where we have significant passive isolation. However as you can see from Figure 3 there is significant energy at frequencies below 10 Hz detected locally. This will certainly excite the stack resonances at 1.2 Hz and 2.1 Hz.

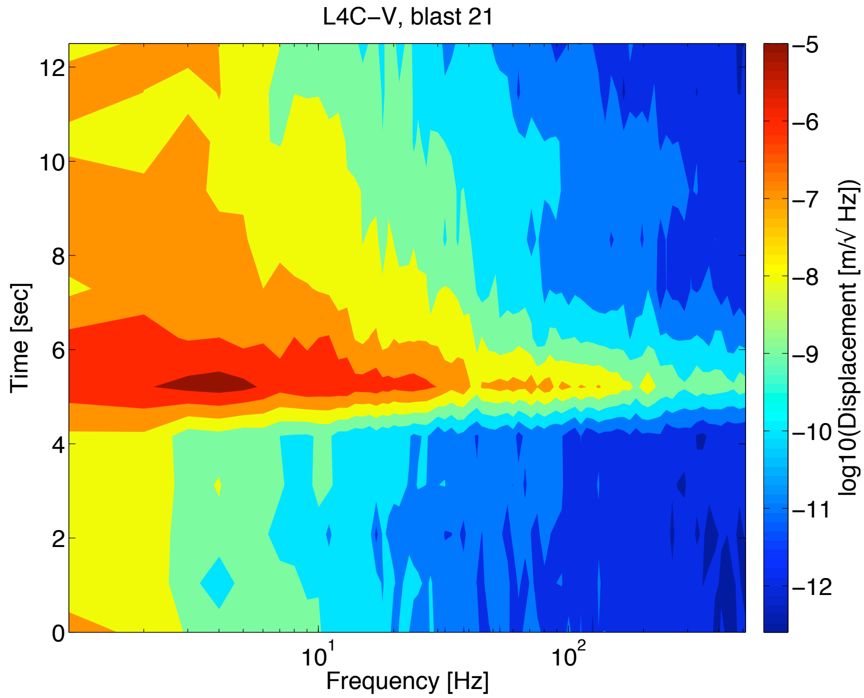


Figure 8: Time-Frequency plot for Blast 21 as seen by the vertical L4C.

4 Conclusions

Figure 9(a) shows the amplitude spectral density of the locally measured motion for all of the blasts which did not saturate our instruments. Figure 9(b) compares the RMS ground motion for the period covering all of the blasts to that of a quiet period between blasts.

Currently the STS-2 seismometers at the end stations have a factor of 3 higher gain than the one at the corner station. We should reduce these gains to guard against saturation. This should allow us to continue to use feedforward sensor correction for more distant blasts. This will also help instrument stability during small earthquakes.

We were quite surprised at the intensity of the blasts, they were far more powerful than initial discussions with the survey crew had led us to believe. It is likely that we will experience on the order of 1 cm/s peak velocities at a distance of 400 feet. We hope to gain access to other data taken during the tests in order to make a more definitive statement. If necessary we can also go into the field again when the survey starts and make more ground motion measurements.

Our plan going forward is:

- Develop a model to predict the waveforms we expect from future blasts. We are hopeful that we can make good predictions at least in the far-field. This effort will include calculating the total pulse energy.
- Acquire extra data from other monitors at the site of the test blasts to fill in gaps in our present understanding.
- Compare the blasts to other large amplitude seismic events which we have experienced on-site in an effort to put their effect into context. Such events include large earthquakes and heavy construction.

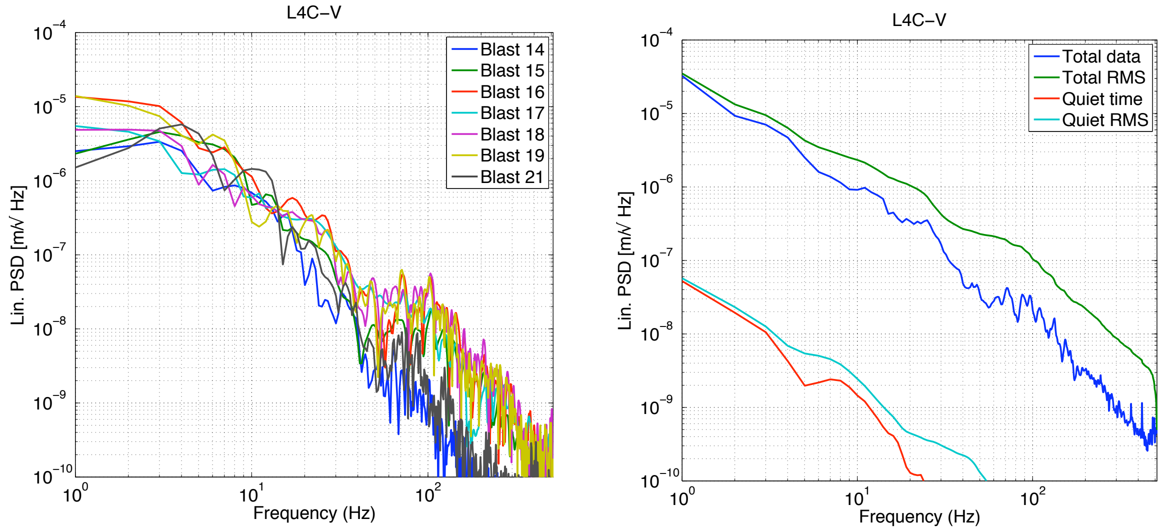
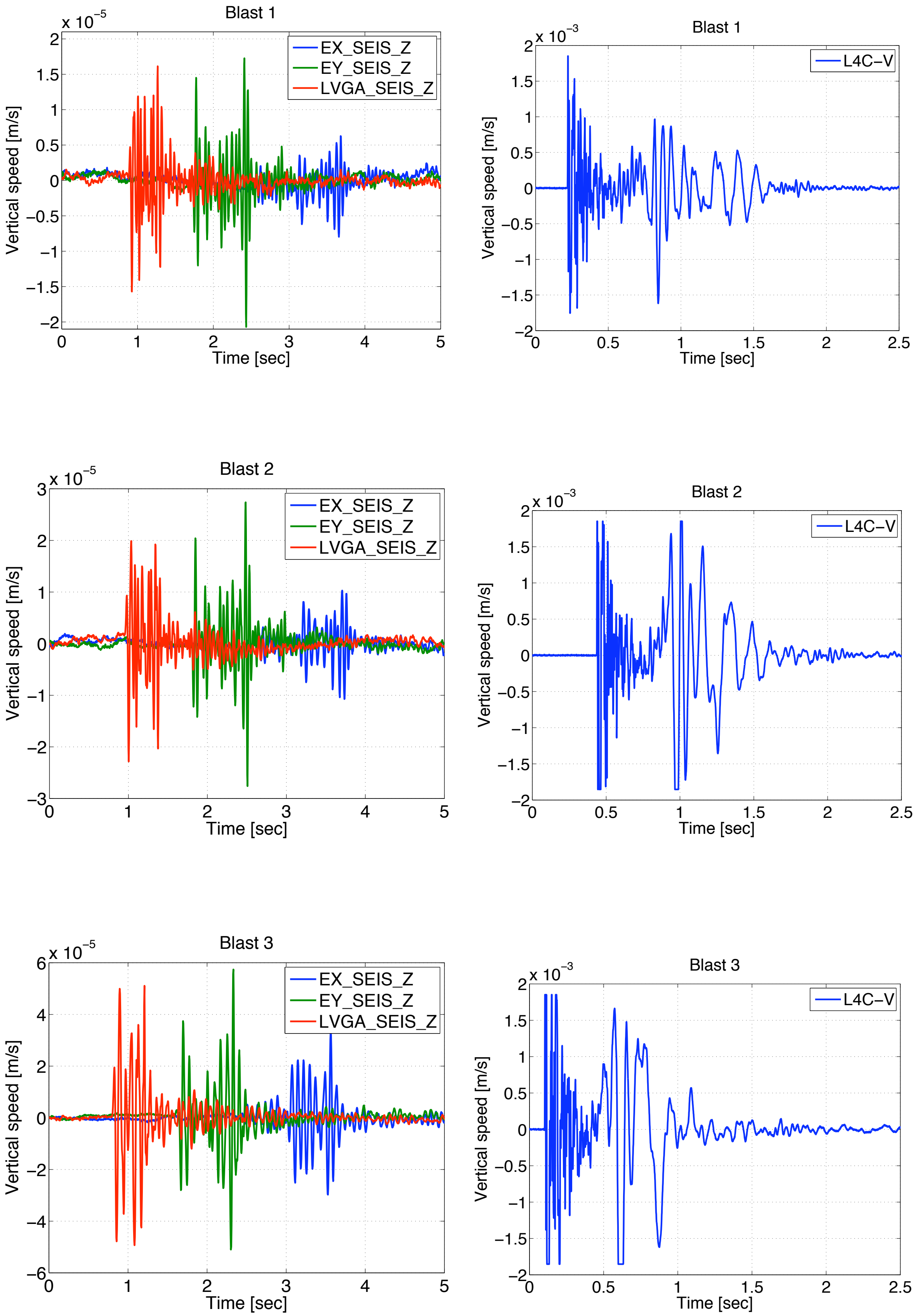


Figure 9: a) ASD for the period covering all blasts and of a quiet period between two blasts. b) ASD of all blasts detected locally without saturation of the vertical L4C.

- Using existing information try to model the motion of the test masses due to the blasts.
- Engage the eLIGO commissioning team in the process, to better understand the impact on the eLIGO schedule.



Blast 1
x 10^−5
Vertical speed [m/s]
Time [sec]
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
Blast 1
x 10^−3
Vertical speed [m/s]
Time [sec]
L4C−V
Blast 2
x 10^−5
Vertical speed [m/s]
Time [sec]
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
Blast 2
x 10^−3
Vertical speed [m/s]
Time [sec]
L4C−V
Blast 3
x 10^−5
Vertical speed [m/s]
Time [sec]
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
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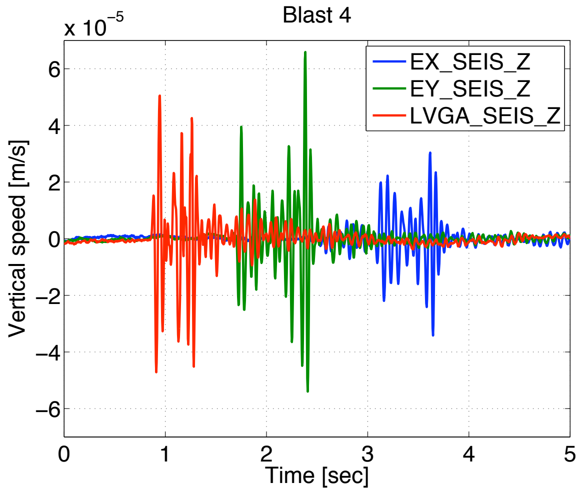
Vertical speed [m/s]
Time [sec]
L4C−V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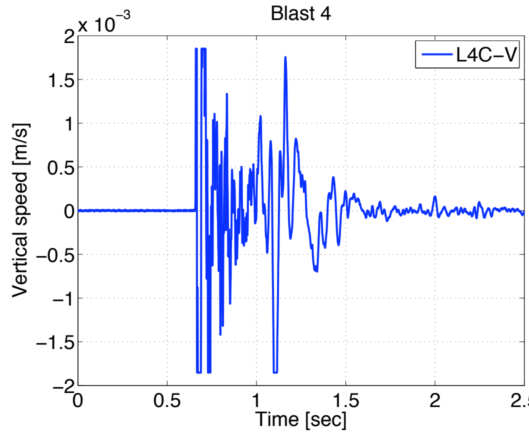
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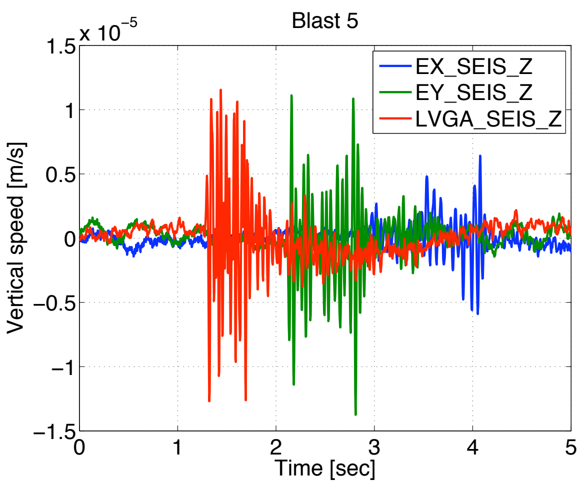
Time [sec]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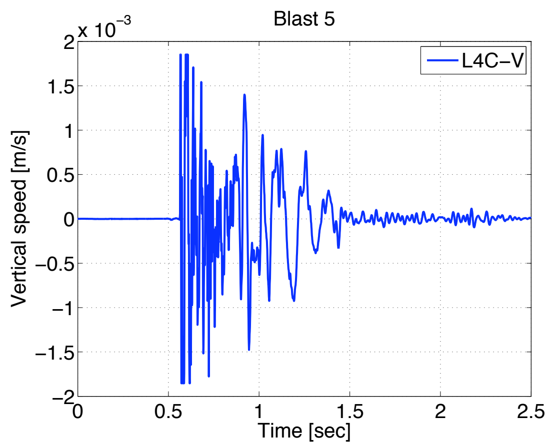
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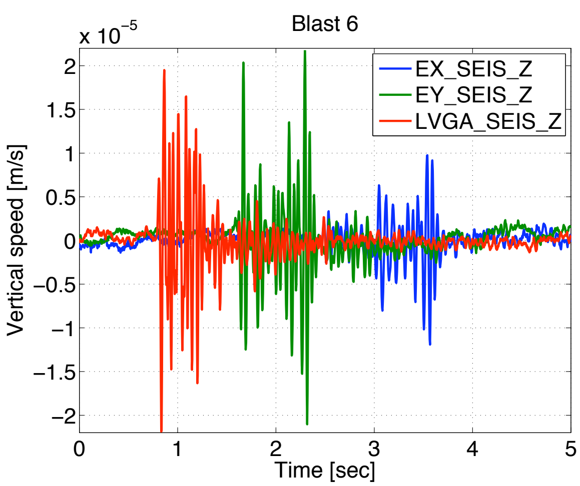
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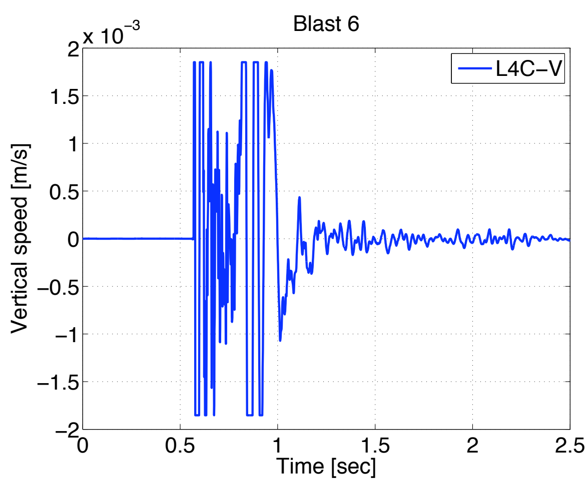
Time [sec]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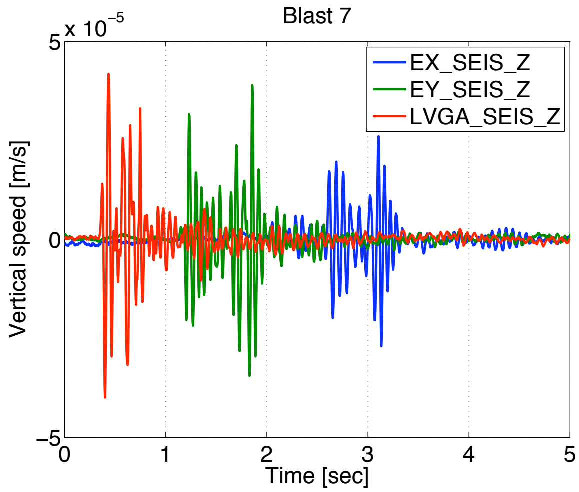
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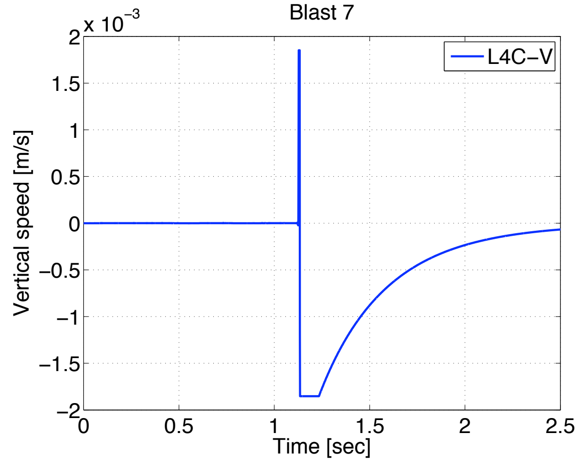
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1.5
2
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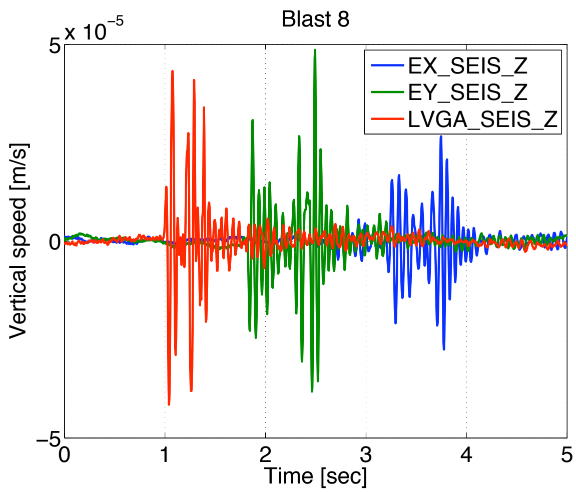
Time [sec]
L4C−V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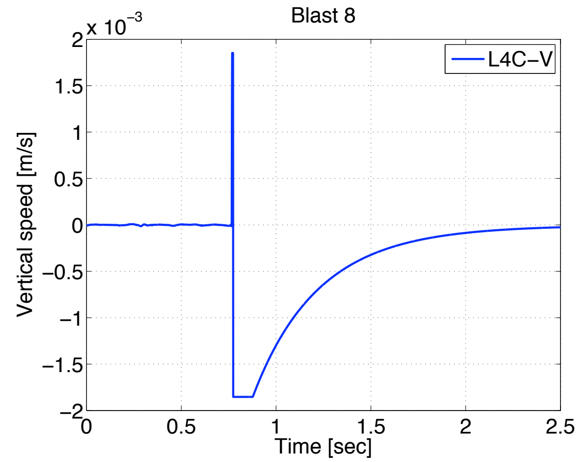
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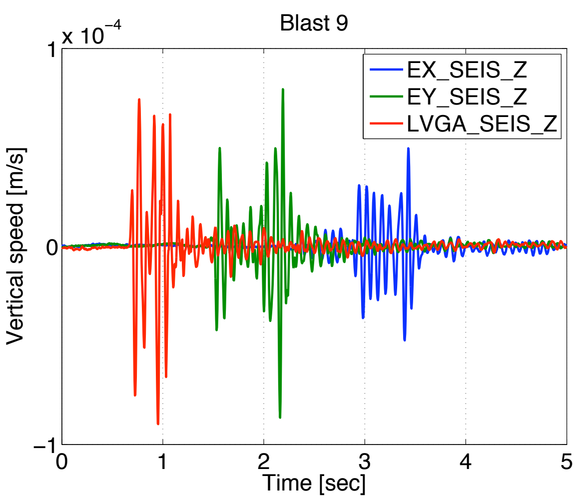
Time [sec]
L4C−V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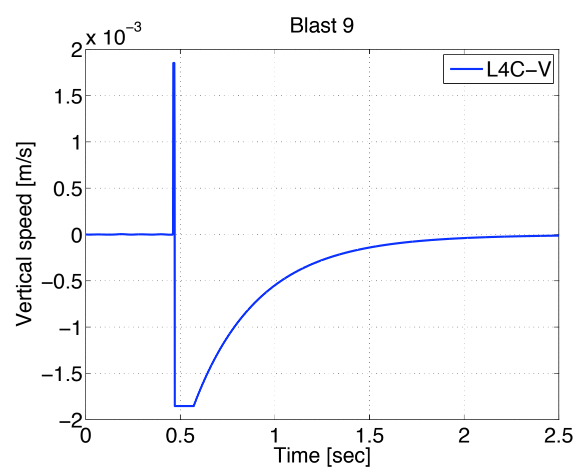
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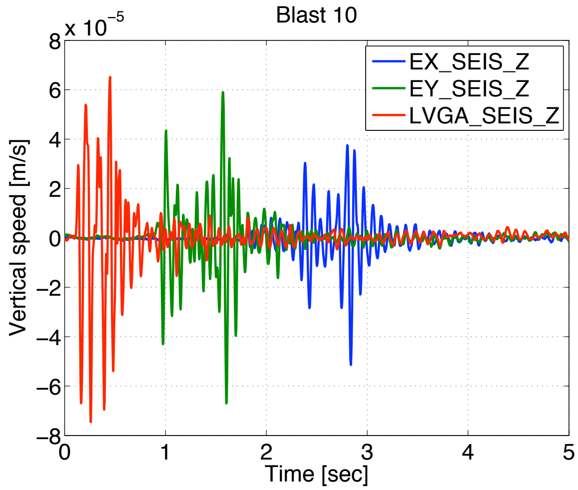
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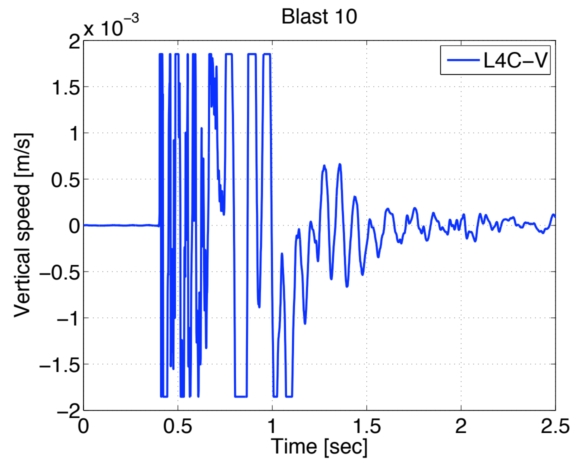
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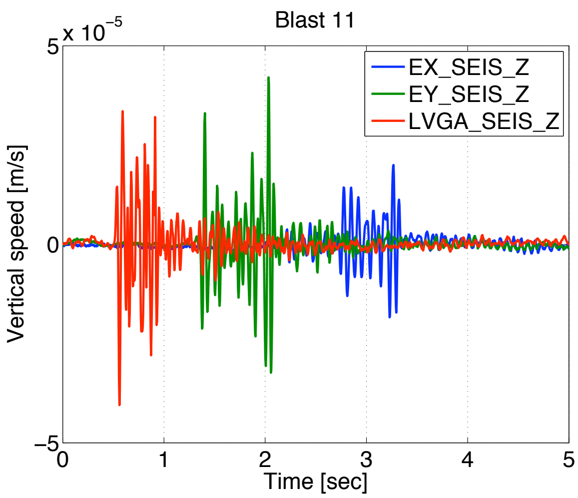
2.5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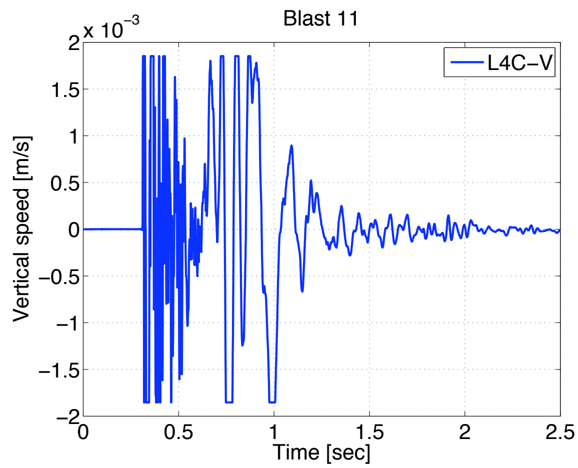
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Time [sec]
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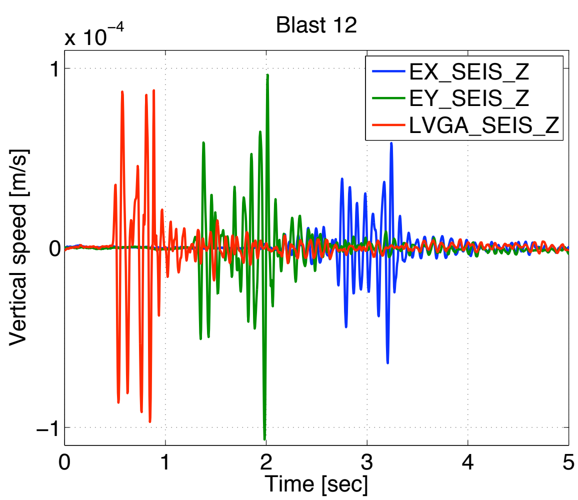
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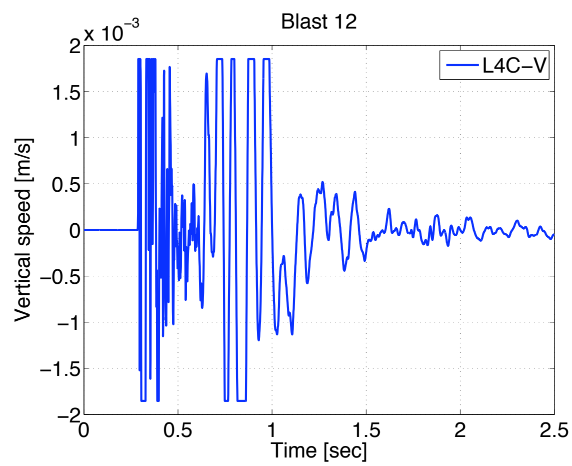
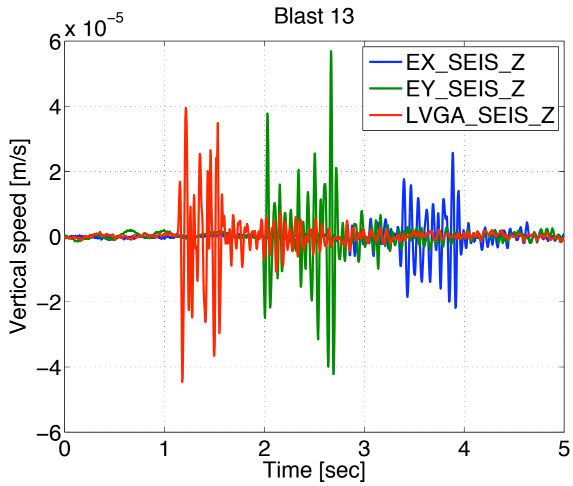
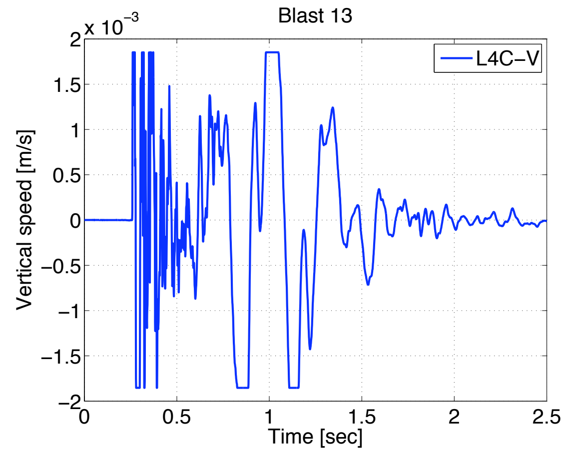
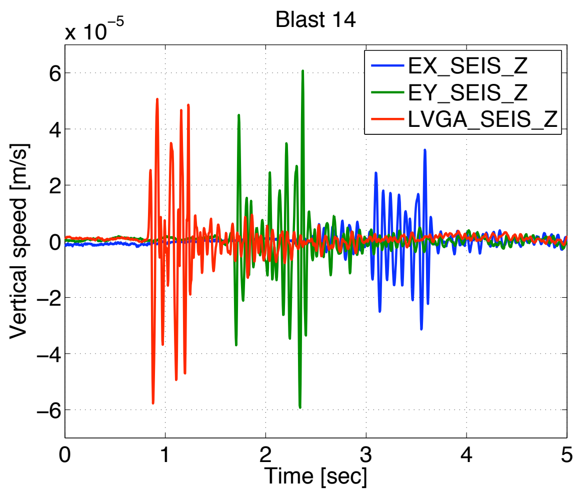
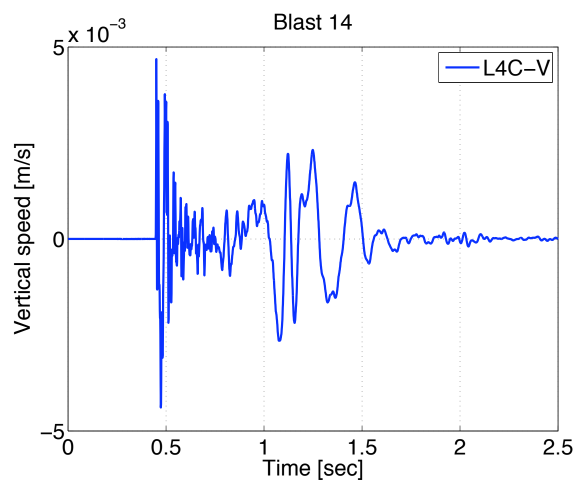
Vertical speed [m/s]
Time [sec]
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
1
0
−1
0
1
2
3
4
5

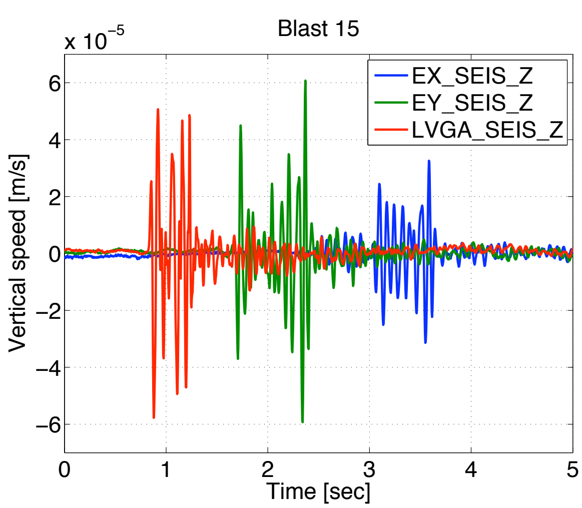

Blast 12
x 10^−3
Vertical speed [m/s]
Time [sec]
L4C−V
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
0
0.5
1
1.5
2
2.5

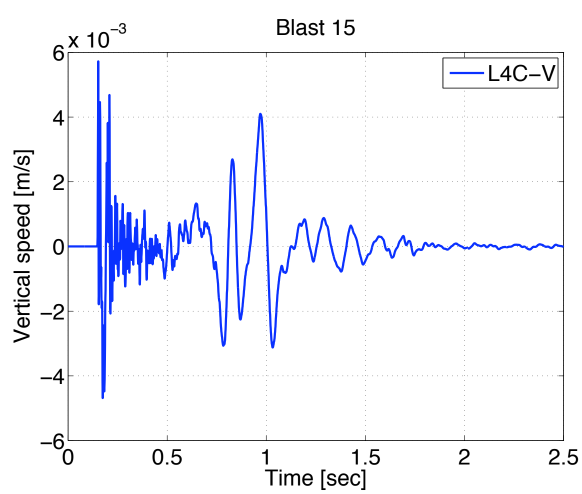

Blast 13
x 10^−5
Vertical speed [m/s]
Time [sec]
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z

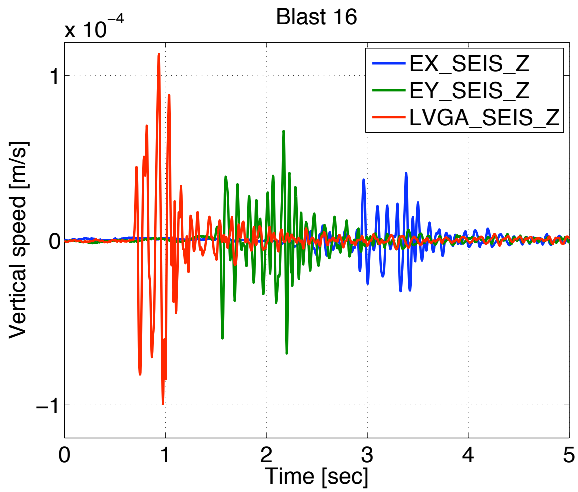

Blast 13
x 10^−3
Vertical speed [m/s]
Time [sec]
L4C−V

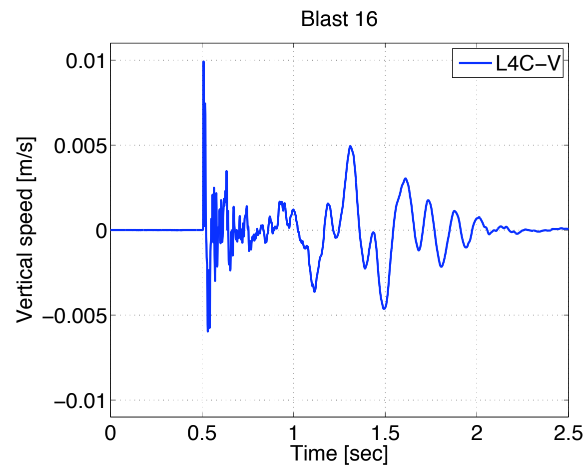

Blast 14
x 10^−5
Vertical speed [m/s]
Time [sec]
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z

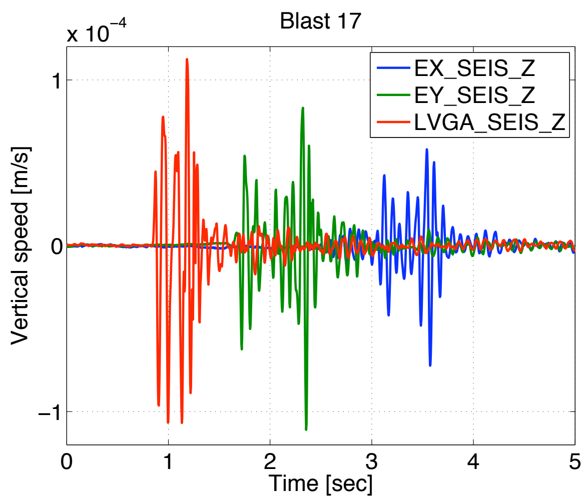

Blast 14
x 10^−3
Vertical speed [m/s]
Time [sec]
L4C−V

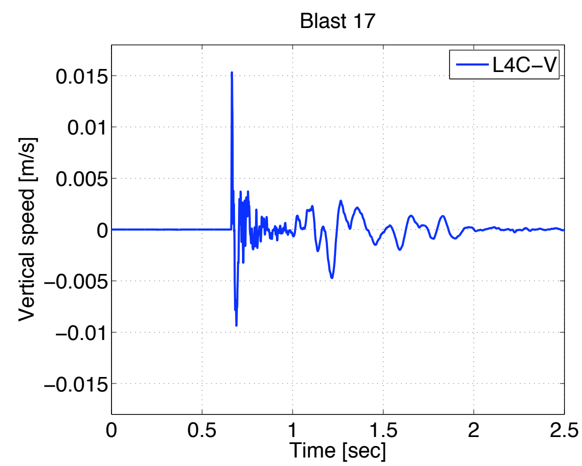

Blast 15
x 10^−5
Vertical speed [m/s]
Time [sec]
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z

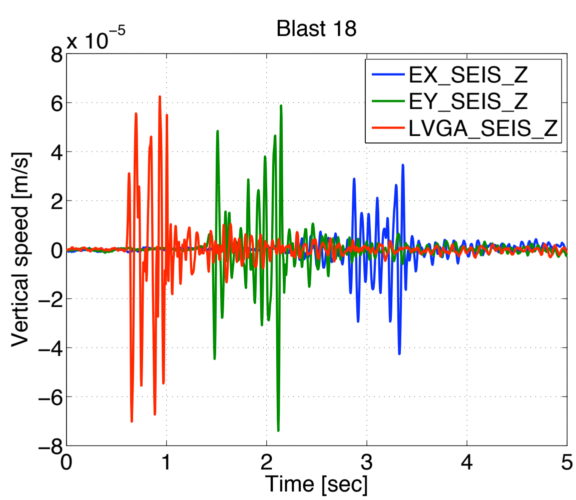

Blast 15
x 10^−3
Vertical speed [m/s]
Time [sec]
L4C−V

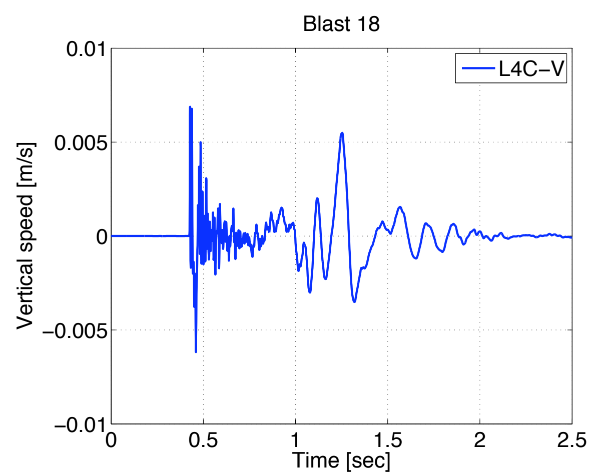

Blast 16
x 10^-4
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
Vertical speed [m/s]
Time [sec]

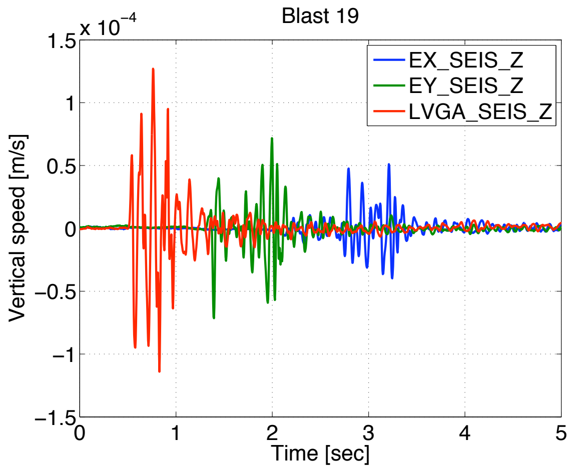

Blast 16
L4C−V
Vertical speed [m/s]
Time [sec]

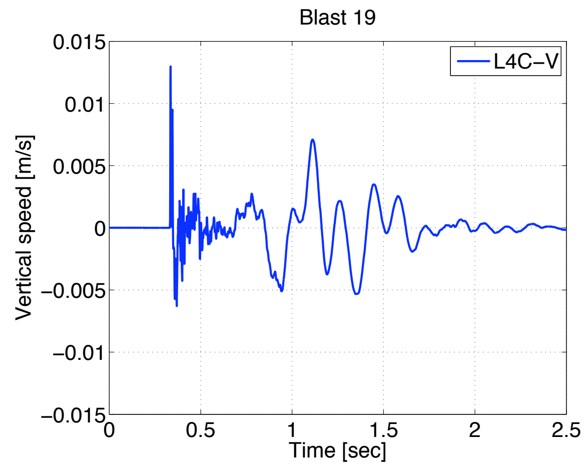

Blast 17
x 10^-4
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
Vertical speed [m/s]
Time [sec]

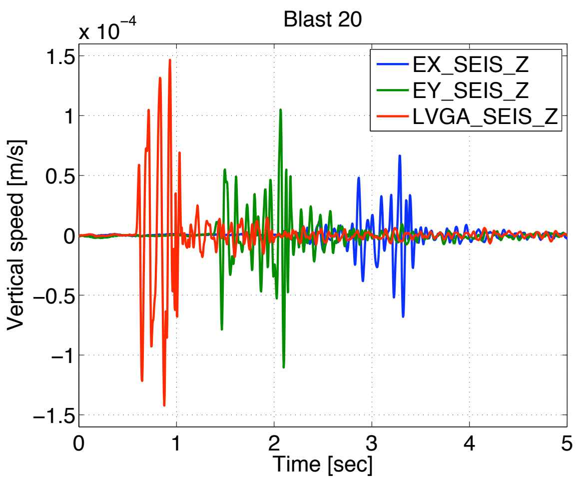

Blast 17
L4C−V
Vertical speed [m/s]
Time [sec]

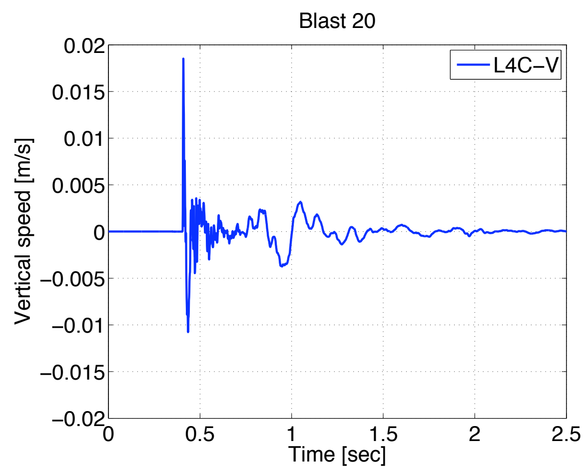

Blast 18
x 10^-5
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
Vertical speed [m/s]
Time [sec]

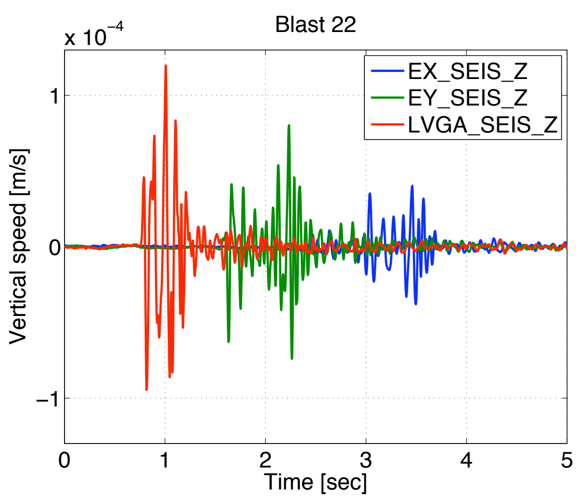

Blast 18
L4C−V
Vertical speed [m/s]
Time [sec]

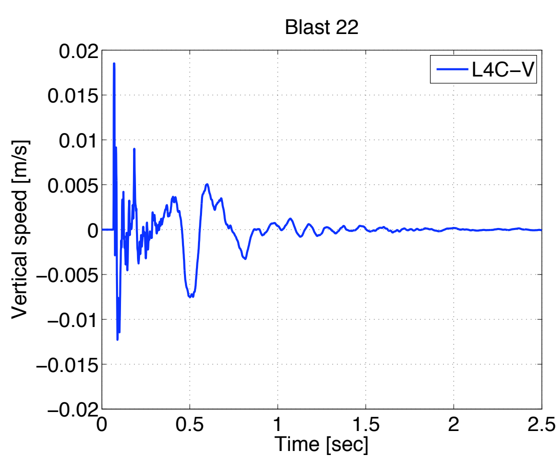

Blast 19
x 10^-4
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
Vertical speed [m/s]
Time [sec]


Blast 19
L4C−V
Vertical speed [m/s]
Time [sec]


Blast 20
x 10^-4
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
Vertical speed [m/s]
Time [sec]


Blast 20
L4C−V
Vertical speed [m/s]
Time [sec]


Blast 22
x 10^-4
EX_SEIS_Z
EY_SEIS_Z
LVGA_SEIS_Z
Vertical speed [m/s]
Time [sec]


Blast 22
L4C−V
Vertical speed [m/s]
Time [sec]