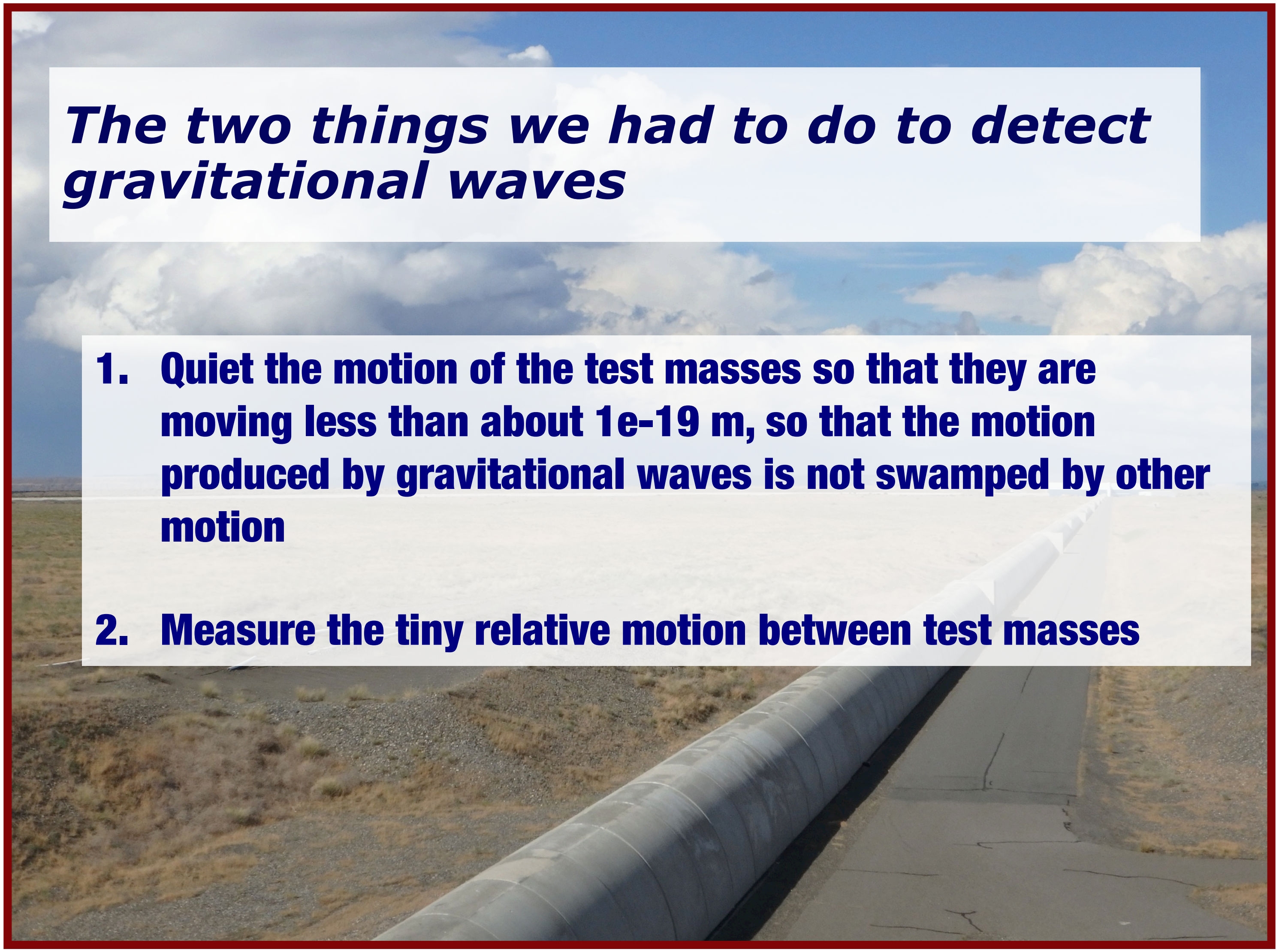
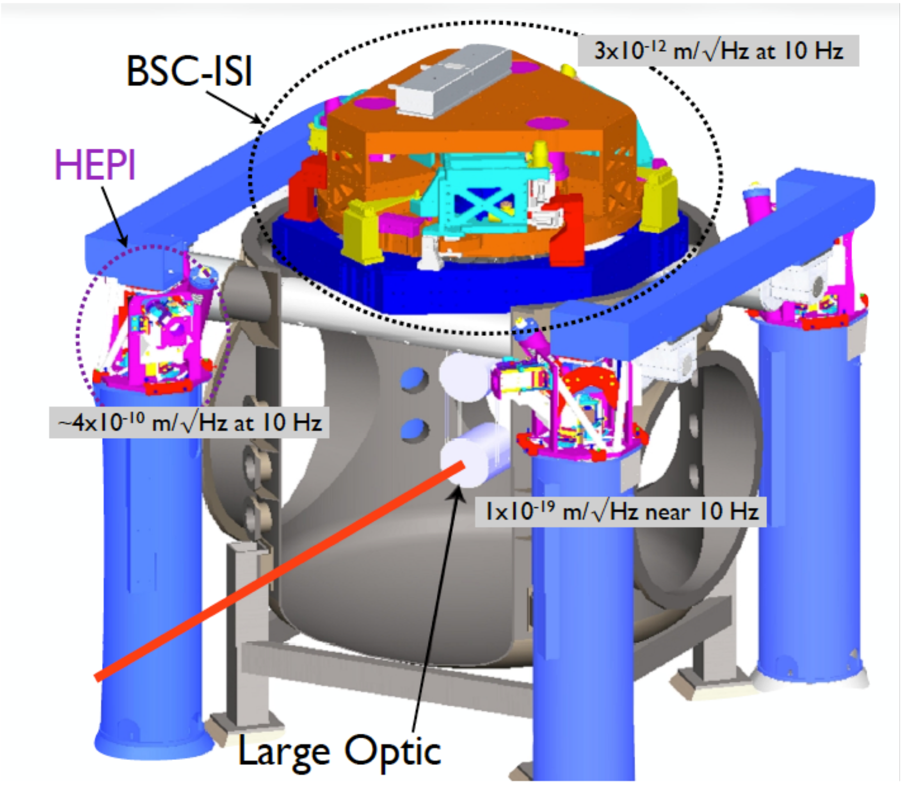
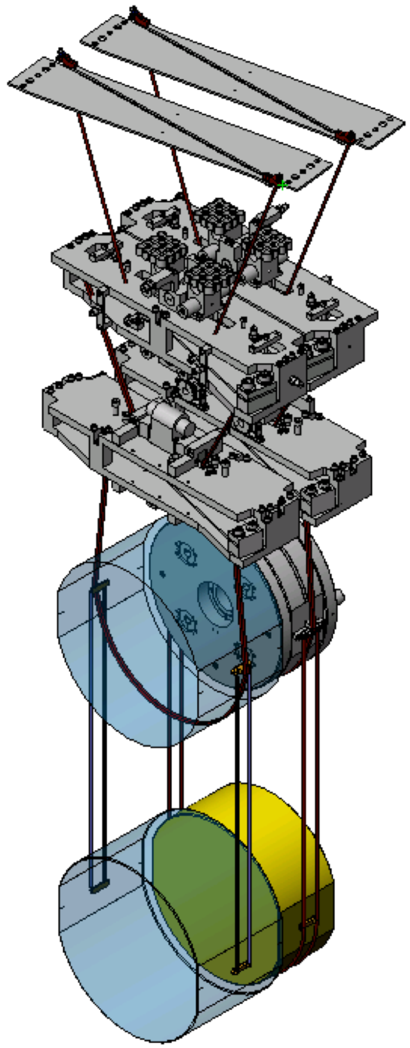
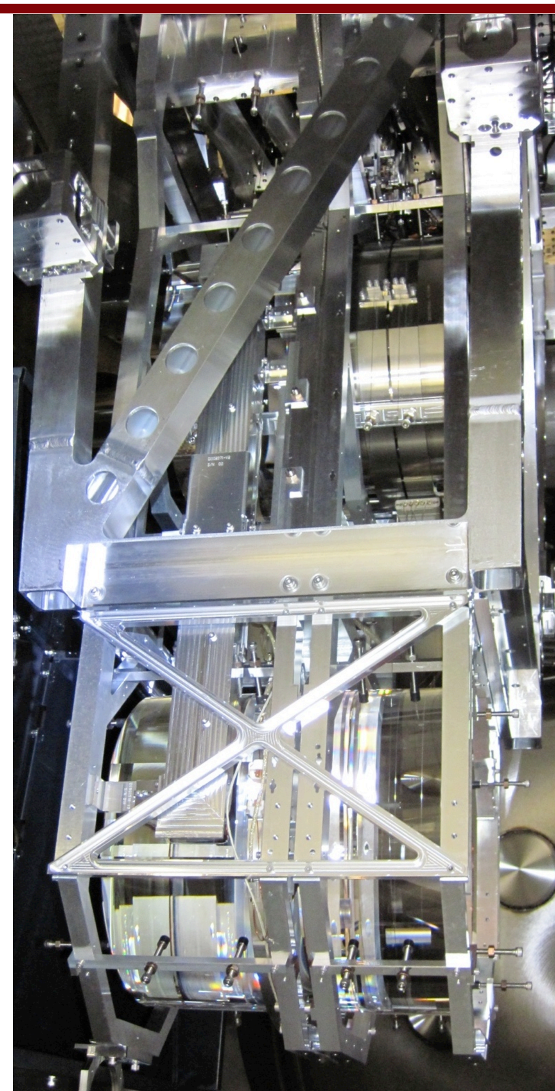
Environmental noise lessons from LIGO for CE site selection

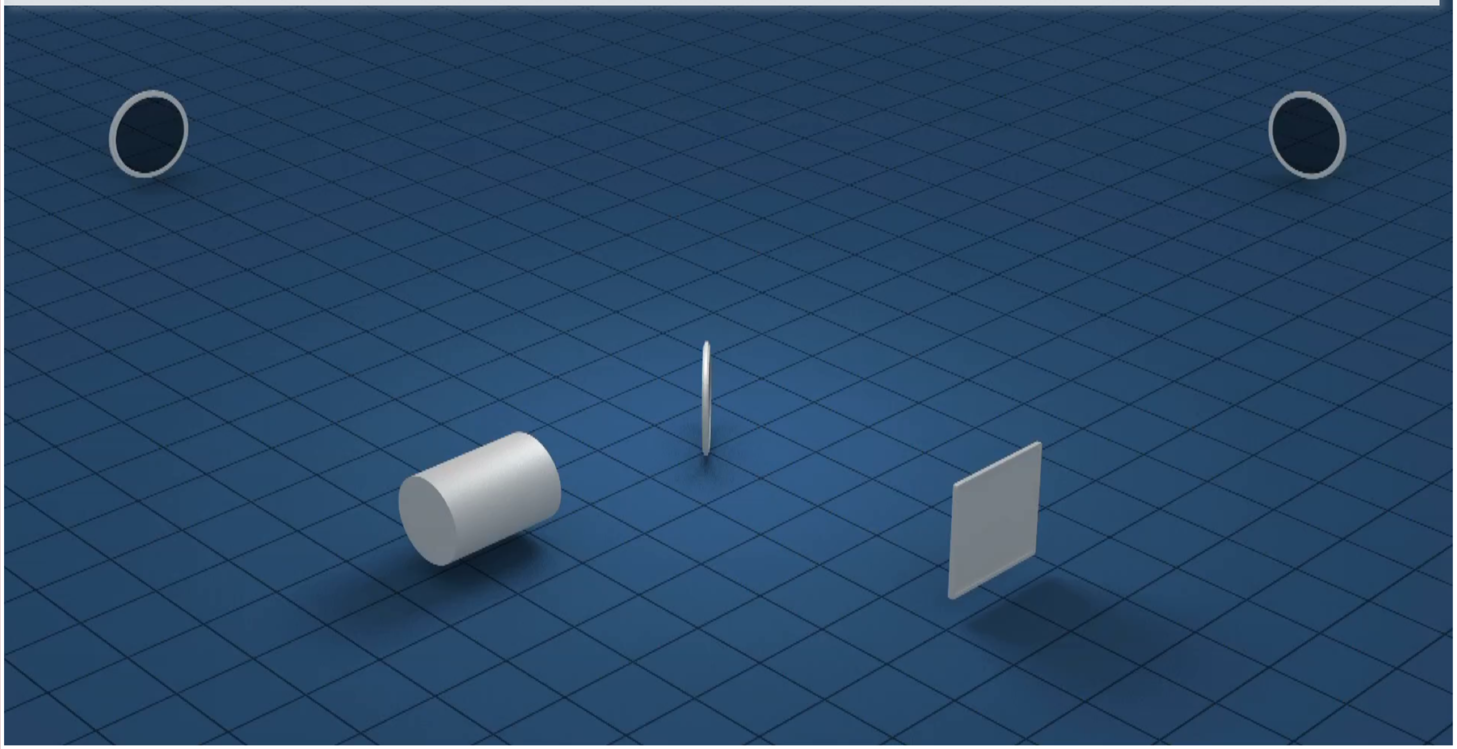

The two things we had to do to detect gravitational waves
1. Quiet the motion of the test masses so that they are moving less than about 1e-19 m, so that the motion produced by gravitational waves is not swamped by other motion
2. Measure the tiny relative motion between test masses

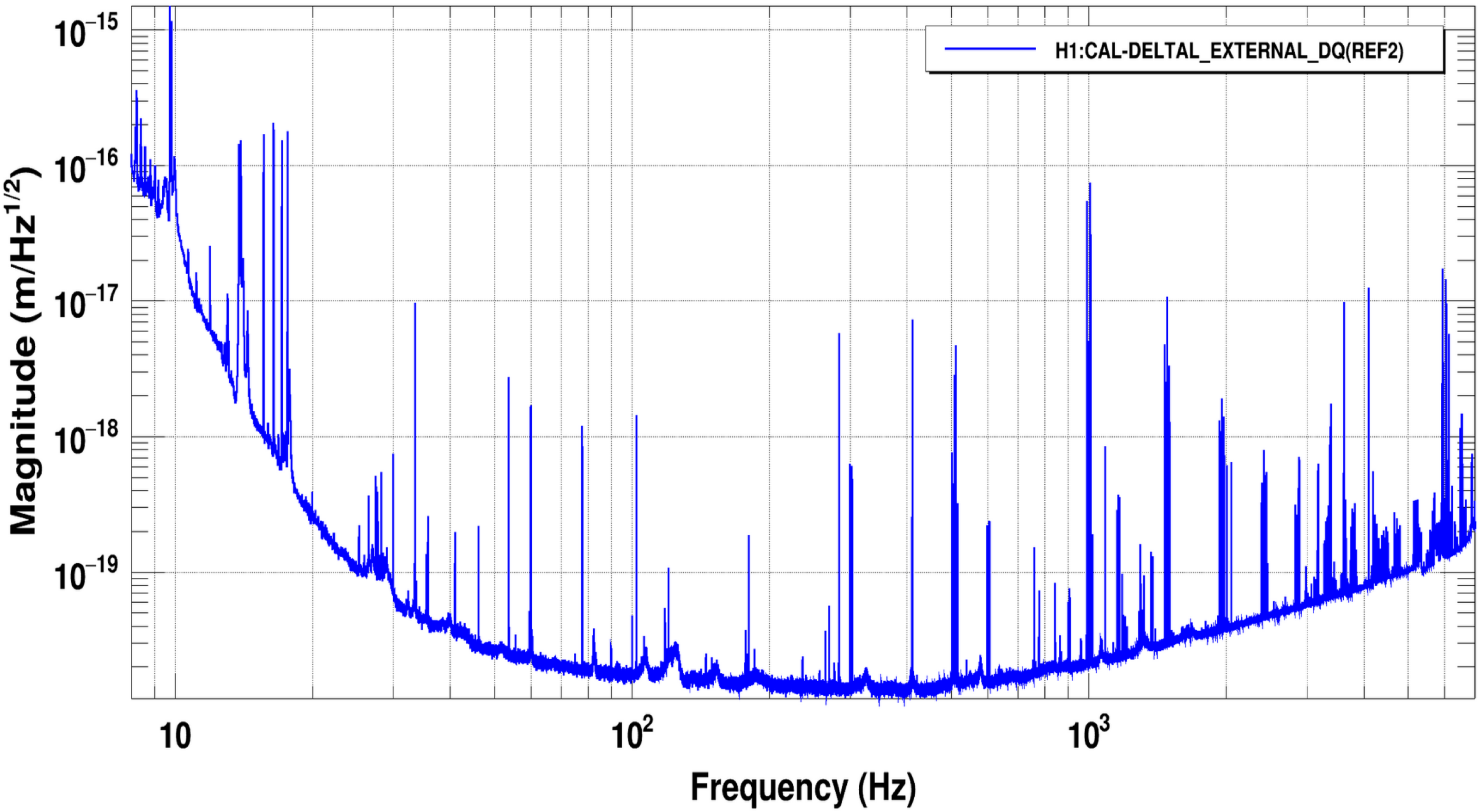
1) Quiet the motion of the mirrors to about 1e-19 m at certain frequencies



2) Measure the tiny distances: interferometers are the best at measuring small differences in distance





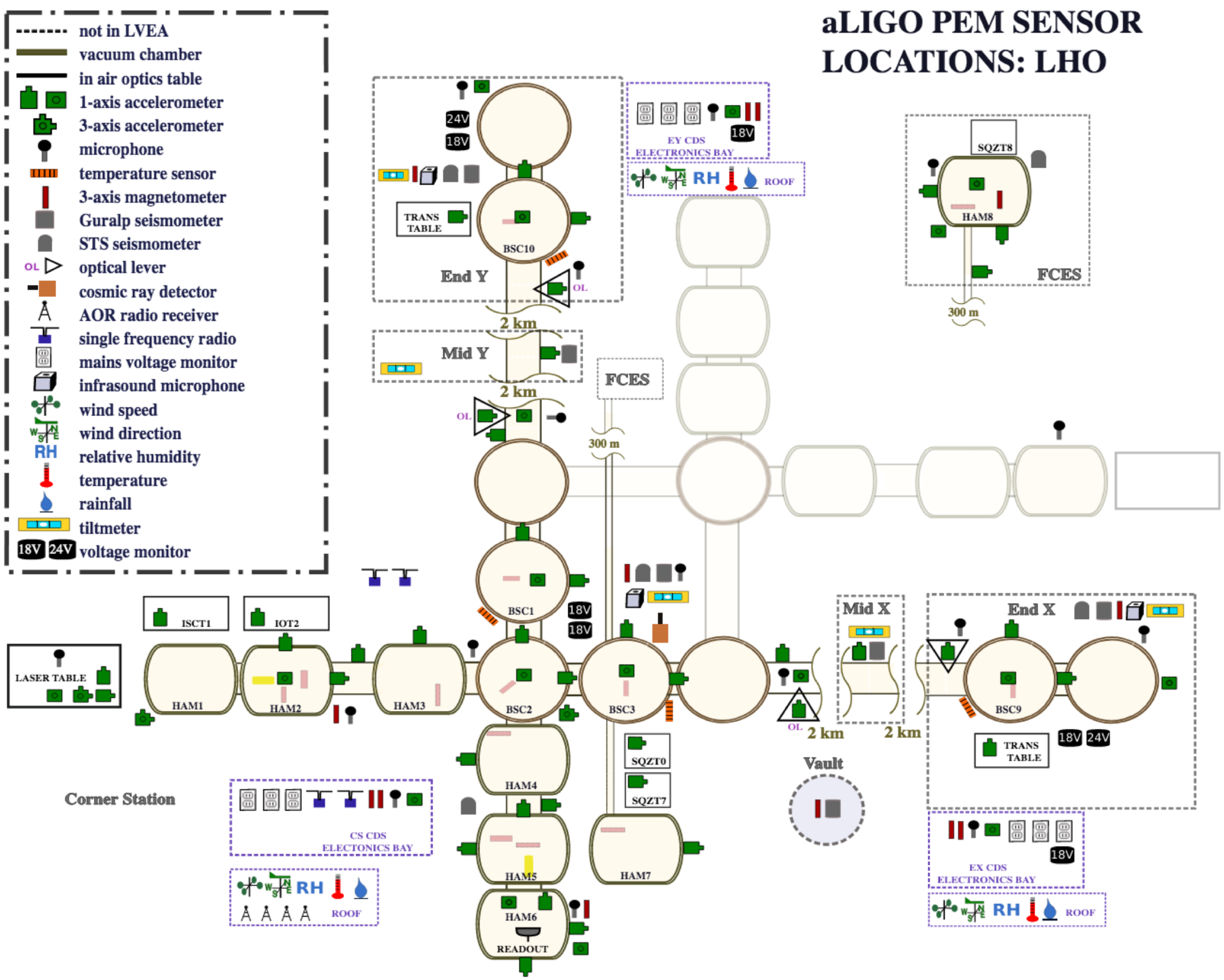
T0=11/04/2024 01:30:00 Avg=100/Bin=2L BW=0.0117098

Seismic

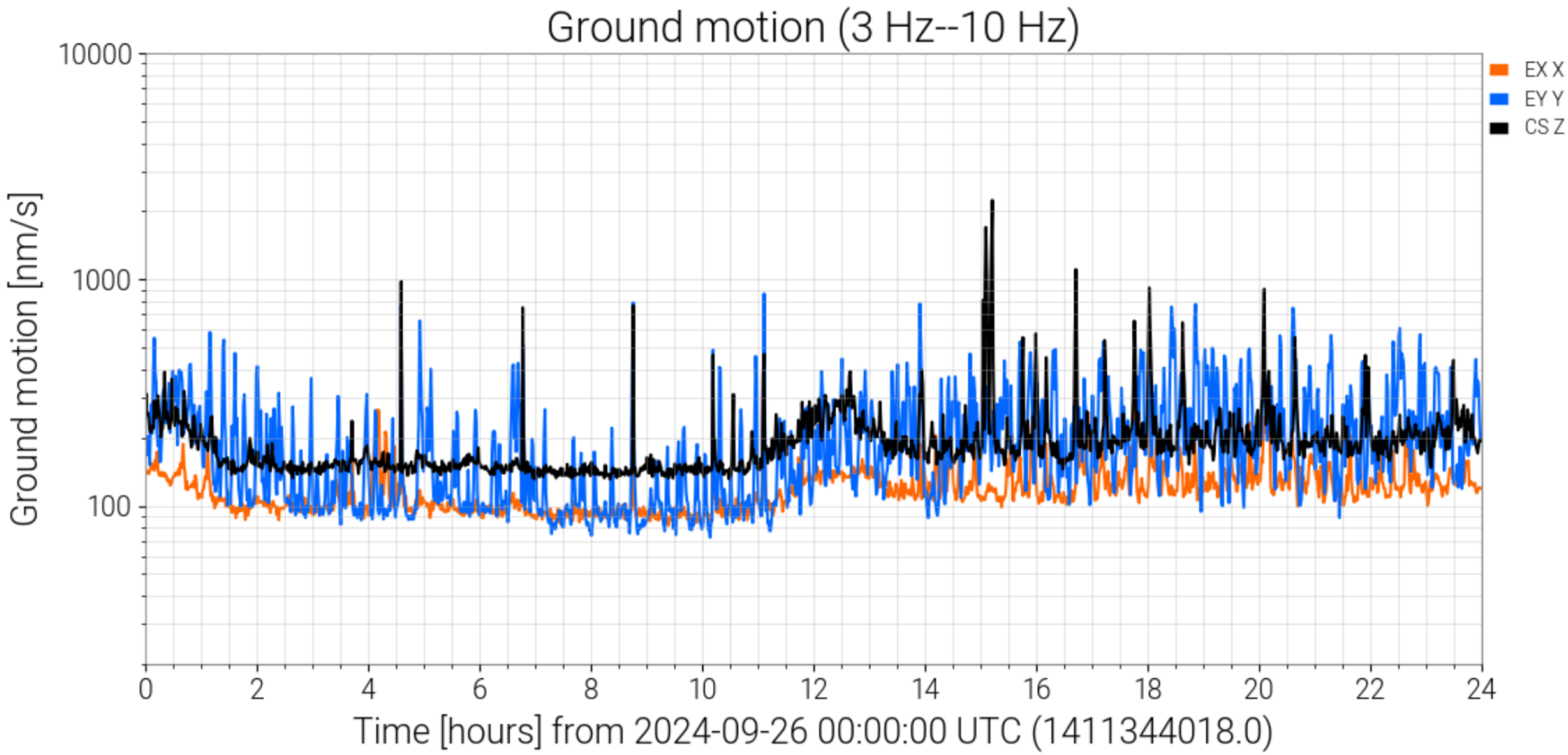
Frequency band	Dominant Noise Source	How it can hurt GW detectors	Coupling
1/day	Earth tides	Changes distance between buildings	Stronger actuators are noisier. Higher velocity between buildings can make main laser light “mimic” GWs (scattered light noise.
Around 0.1 Hz	Ocean waves: microseismic peak	Same as above and also some relative motion within buildings.	Same as above: scattered light noise is one of the worst non-fundamental noise sources.
0.1 – 10 Hz and above	Wind	Shakes buildings, tilts ground	More motion gets through isolation, moving optics, and scattered light noise, also direct Newtonian coupling to TMs
1-30 Hz	Anthropogenic noise Trains, trucks, cars, OHVs, construction equipment, wind farms, dams	Motion within a building	Moving test masses and other optics, and scattered light noise, also direct Newtonian coupling to TMs
30 Hz to 7000 Hz	On site sources, HVAC, motors, people	Same as above	Same as above

Magnetic

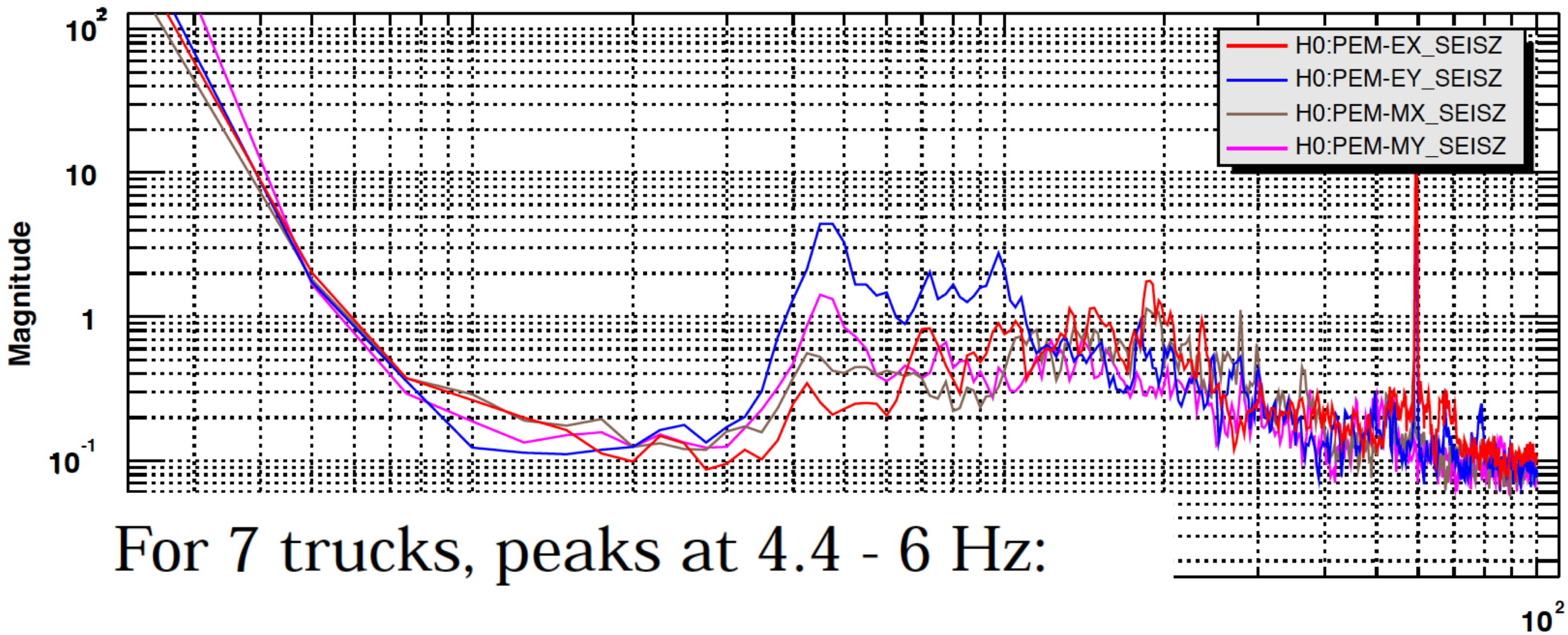
Frequency band	Dominant Noise Source	How it can hurt GW detectors	Coupling
1–1000 Hz and up	Electric currents	magnetic coupling moves optics and other components	Actuation permanent magnets and magnetized components
1-1000 Hz and up but increasing with frequency	Electric currents	Induced currents add noise, mainly to analog signals	Electronic components and cables


aLIGO PEM SENSOR LOCATIONS: LHO
not in LVEA
vacuum chamber
in air optics table
1-axis accelerometer
3-axis accelerometer
microphone
temperature sensor
3-axis magnetometer
Guralp seismometer
STS seismometer
OL optical lever
cosmic ray detector
AOR radio receiver
single frequency radio
mains voltage monitor
infrasound microphone
wind speed
wind direction
RH relative humidity
temperature
rainfall
tiltmeter
18V 24V voltage monitor
24V
18V
TRANS TABLE
BSC10
End Y
OL
EY CDS ELECTRONICS BAY
RH
ROOF
SQZT8
HAM8
FCES
300 m
2 km
Mid Y
FCES
300 m
2 km
OL
BSC1
18V
18V
ISCT1
IOT2
LASER TABLE
HAM1
HAM2
HAM3
BSC2
BSC3
HAM4
SQZT0
SQZT7
HAM5
HAM7
HAM6
READOUT
Corner Station
CS CDS ELECTRONICS BAY
RH
ROOF
Mid X
End X
OL
2 km
2 km
BSC9
TRANS TABLE
18V
24V
Vault
EX CDS ELECTRONICS BAY
18V
RH
ROOF


2 km
1.15 mi
LIGO Hanford
Observatory
Recently viewed
Energy Northwest
Geneva
Junction
Hanford Rte 10
Rte 4 S
240
Measure distance
Click on the map to add to your path
Total distance: 1.15 mi (1.84 km)



Ground motion (3 Hz--10 Hz)
10000
1000
100
Ground motion [nm/s]
EX X
EY Y
CS Z
0
2
4
6
8
10
12
14
16
18
20
22
24
Time [hours] from 2024-09-26 00:00:00 UTC (1411344018.0)

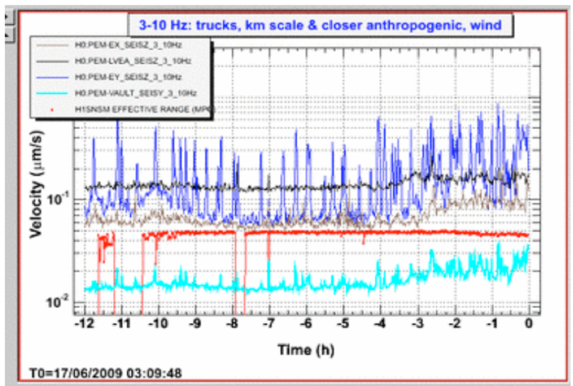


For 7 trucks, peaks at 4.4 - 6 Hz:

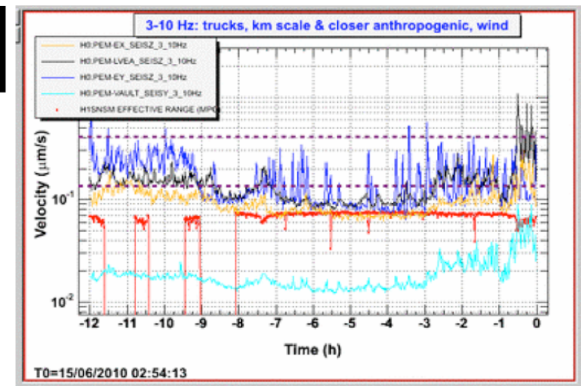
$$Q = 68 \pm 12$$

3-10 Hz peak seismic noise down by >2 with resurfacing of highway 240

Before



After



Percentiles from sorted 1 minute trend values (maxima) of H0:PEM-EY_SEISZ_3_10Hz for 150 days starting Nov. 2

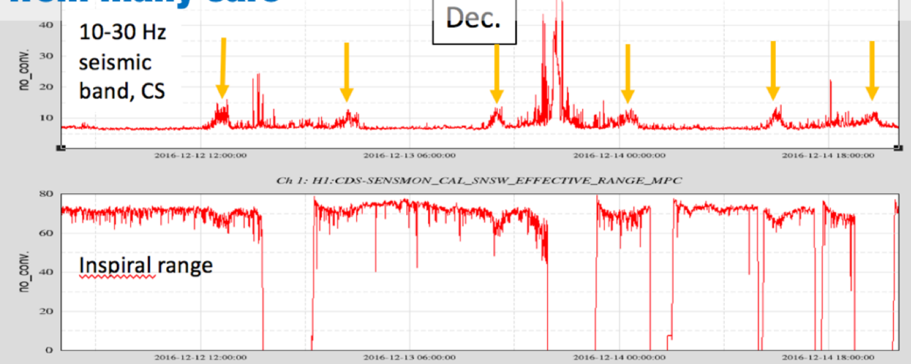
Percentile	Amplitude 2008-2009	Amplitude 2009-2010	After paving/ before paving
99.9	23982	8637	0.36
99	5560	2582	0.46
95	2630	1205	0.46
90	1633	769	0.47
75	575	309	0.54
50	251	152	0.61

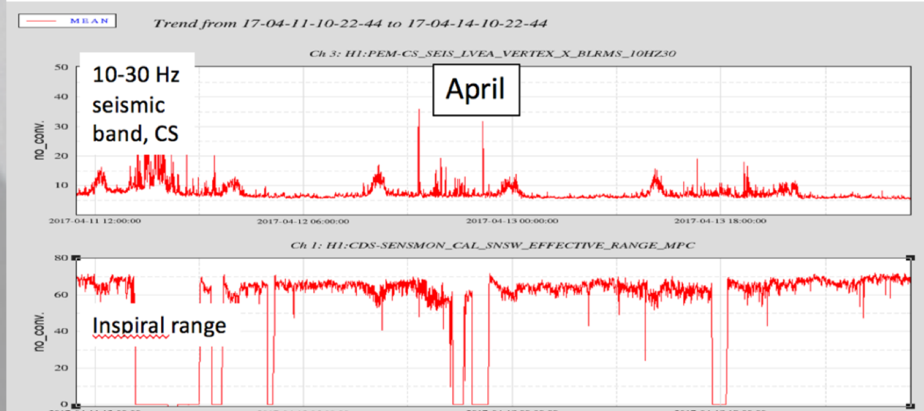
Maximum 10 Hz Newtonian noise estimates down by >2 for aLIGO

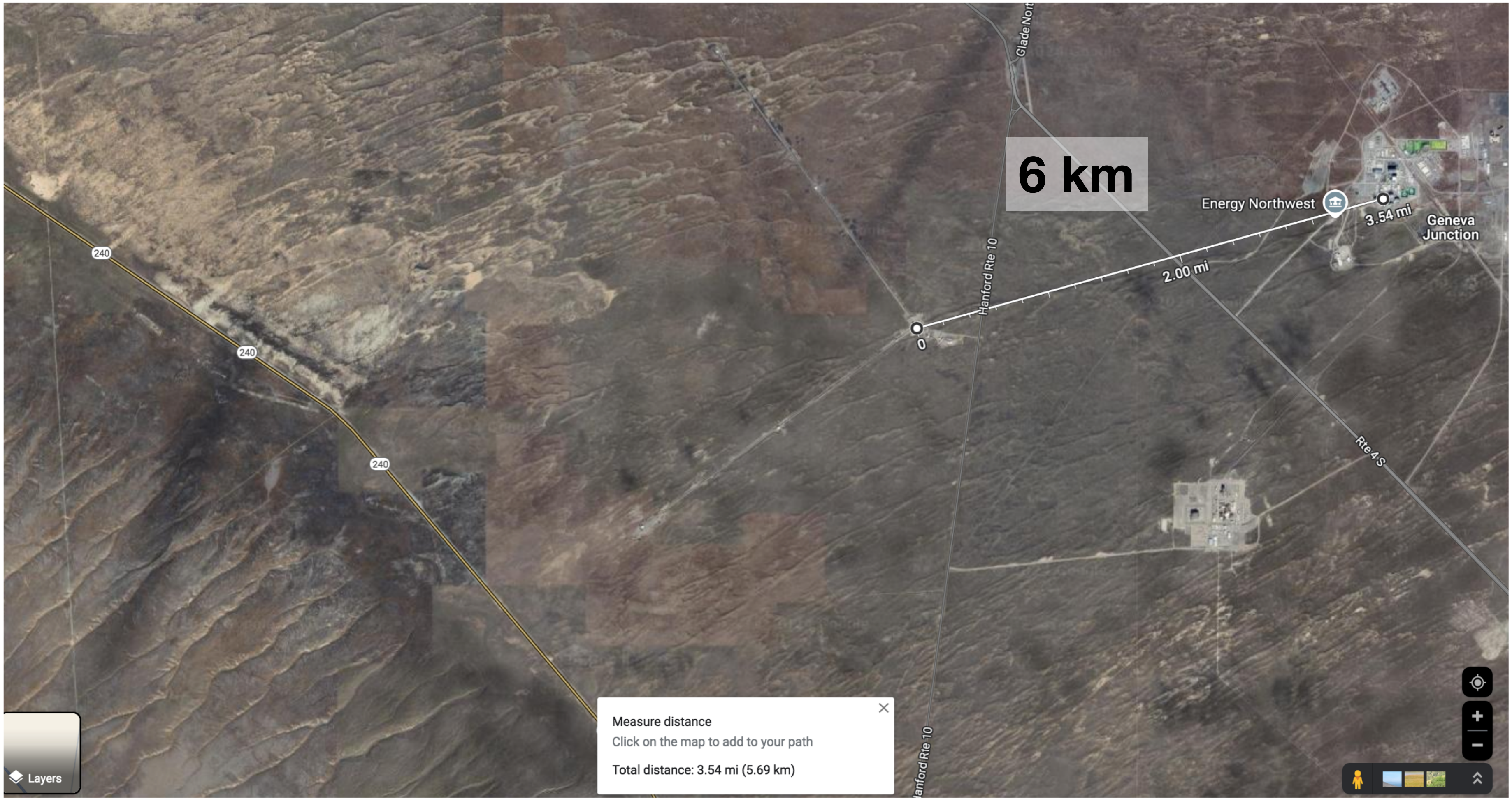
LHO noise from fire pump, HVAC, traffic

B. Berger and other DetChar DQ shifters noticed seismic-associated events in DARM: trucks, rush hour traffic, HVAC, fire pump, all reduced range.

Work-day seismic peaks, and range dips, happen at rush hour and follow daylight savings, gaussian from many cars







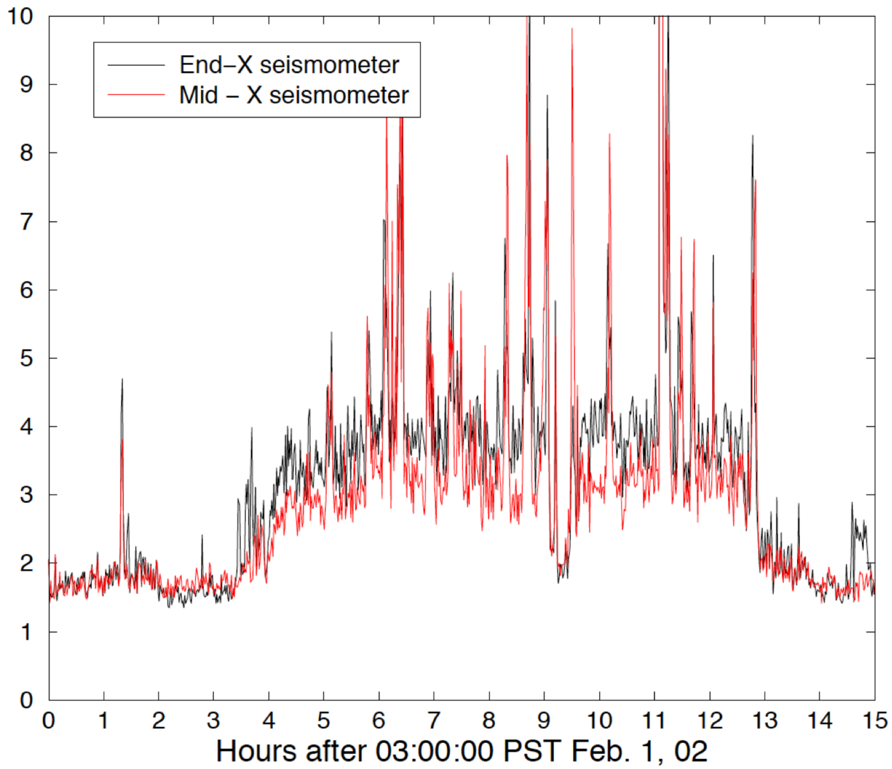
6 km
Energy Northwest
3.54 mi
2.00 mi
0
Geneva
Junction
Hanford Rte 10
Glade North
Rte 4S
240
Measure distance
Click on the map to add to your path
Total distance: 3.54 mi (5.69 km)
Layers

Mobile seismometer suggested cooling towers.

Motor monitors and gear-teeth ratios allowed calculation of frequency for each of 36 fans: nearly all fell within our peak.


10 km
May Junction
Savage Island
Columbia River
240
240
5.68 mi
Geneva Junction
Columbia River
Measure distance
Click on the map to add to your path
Total distance: 5.68 mi (9.14 km)

1-3 Hz band



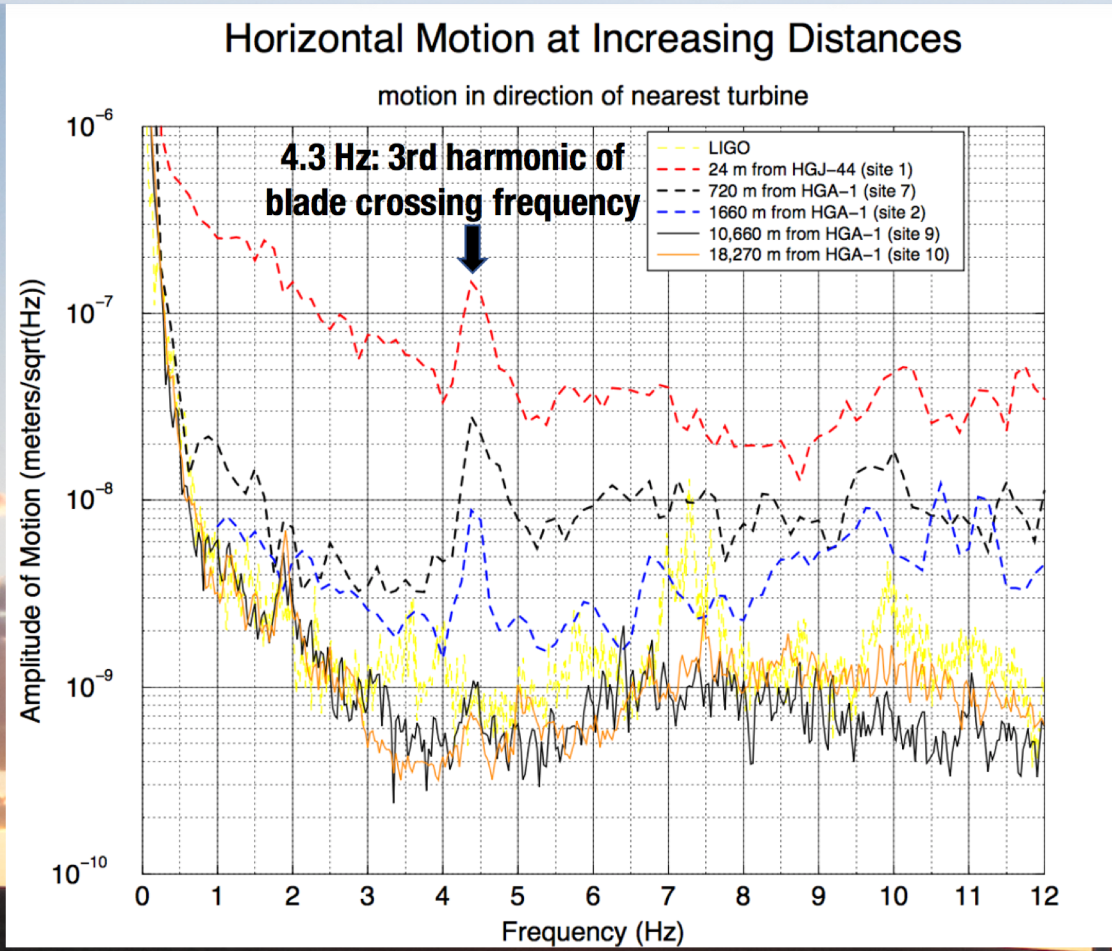
Traced to Vitrification Plant Project

10 km from X-end, up to 5000 workers expected during 5 year project

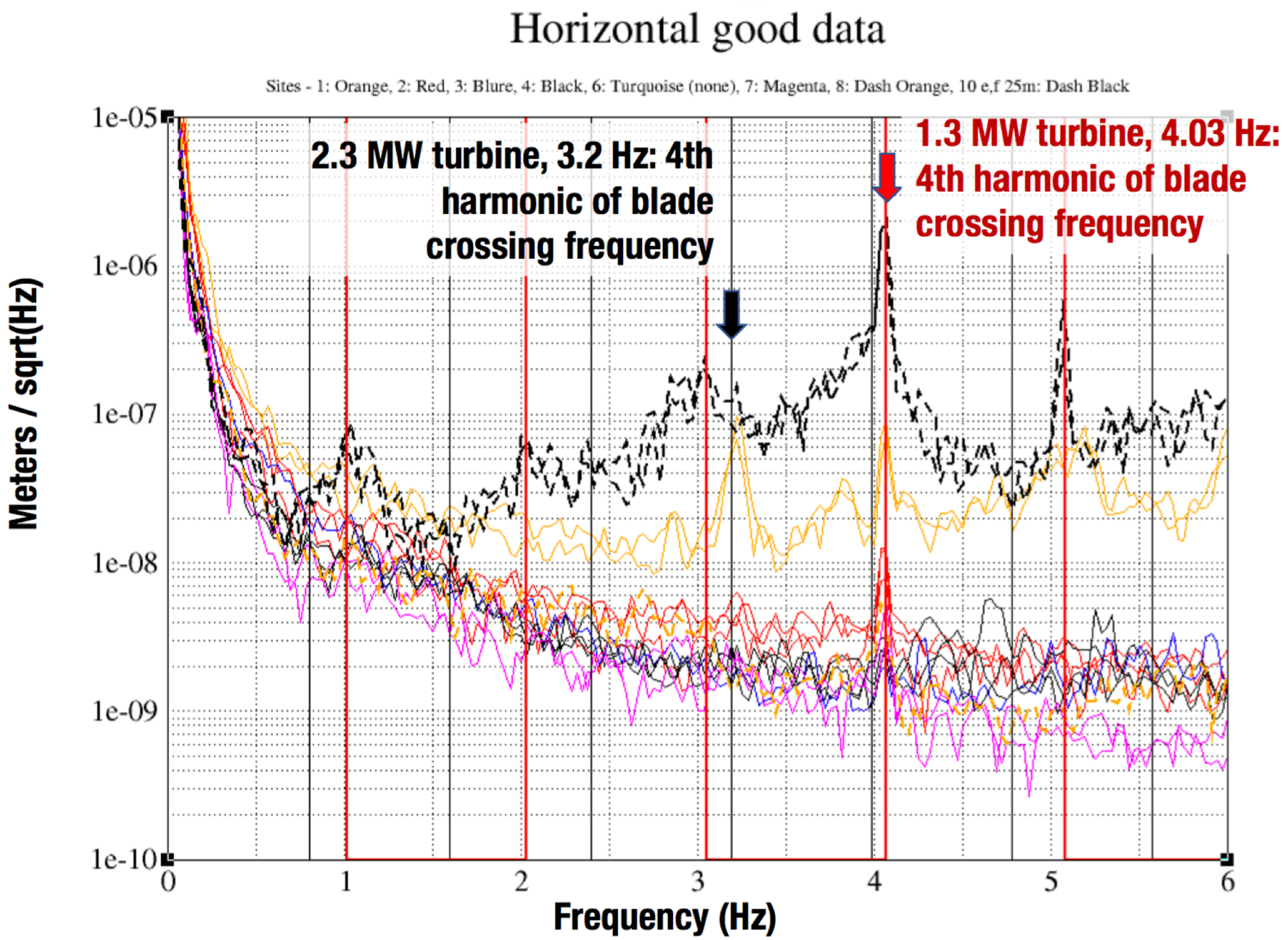
Predicting seismic noise from wind farms for a current proposal

Robert Schofield, LIGO-T1900746-v1

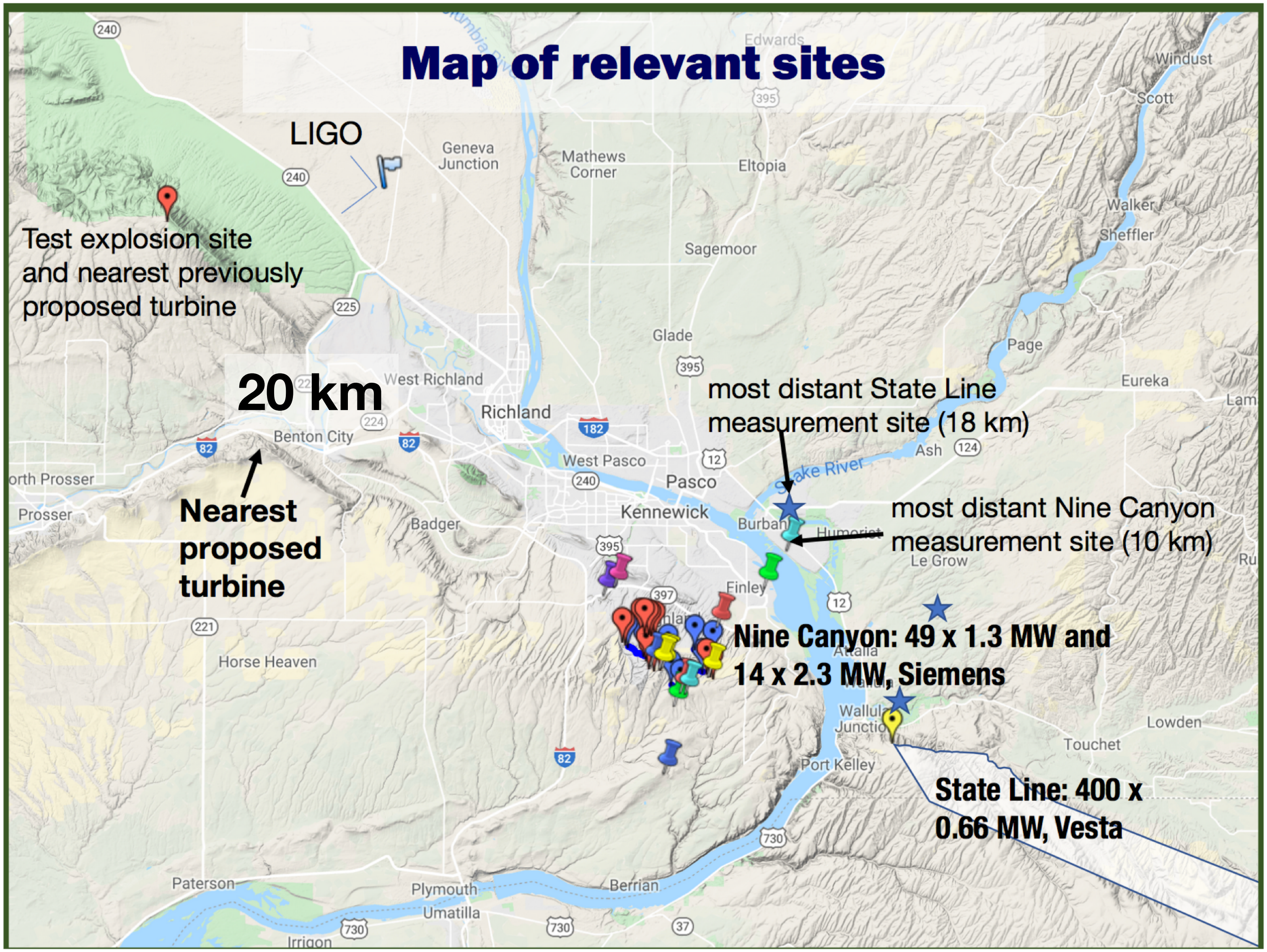
Sample of seismic measurements around State Line wind farm (State Line report, T020104-x0)



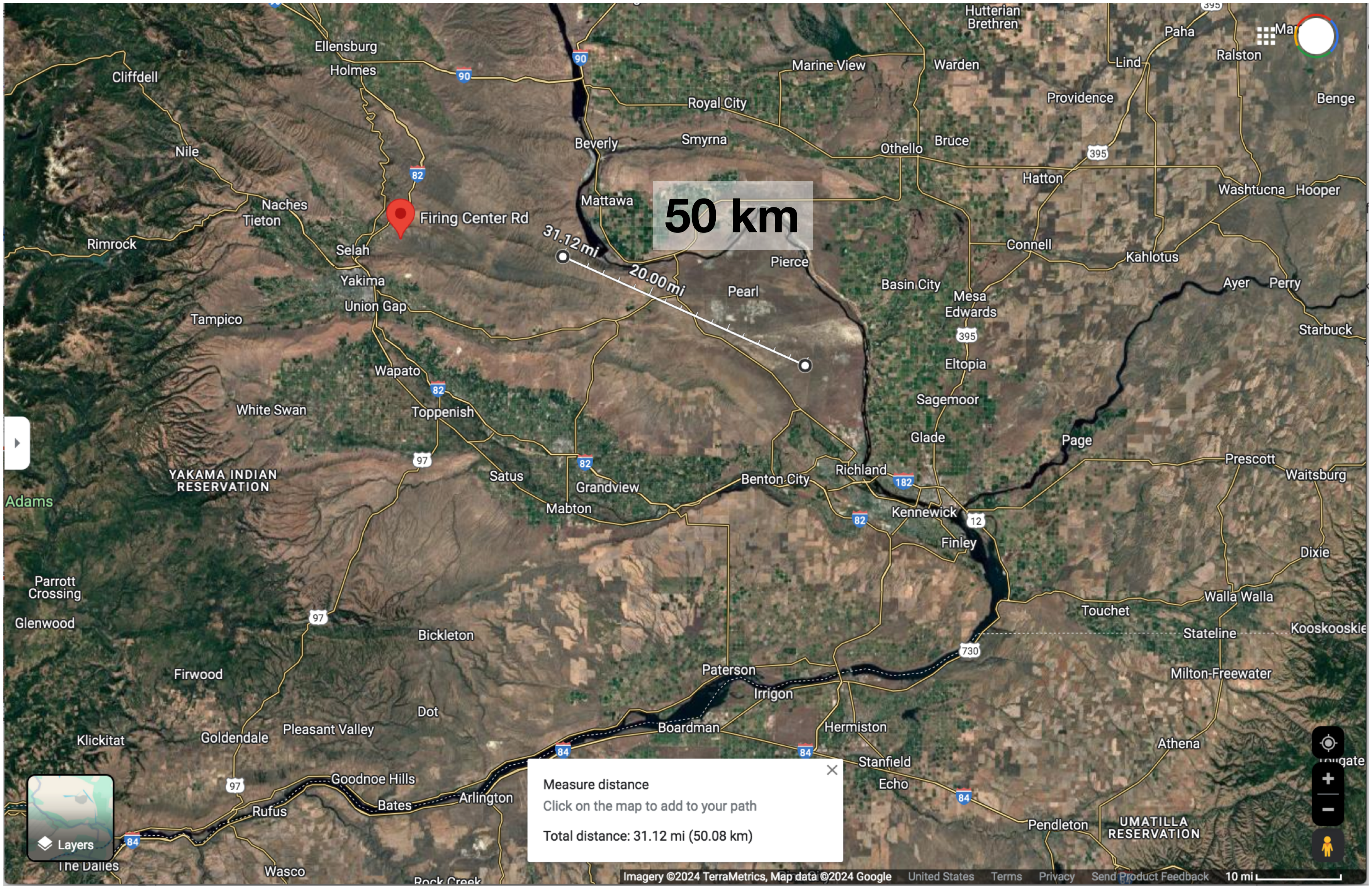
Sample of newer seismic measurements around Nine Canyon wind farm



20 km



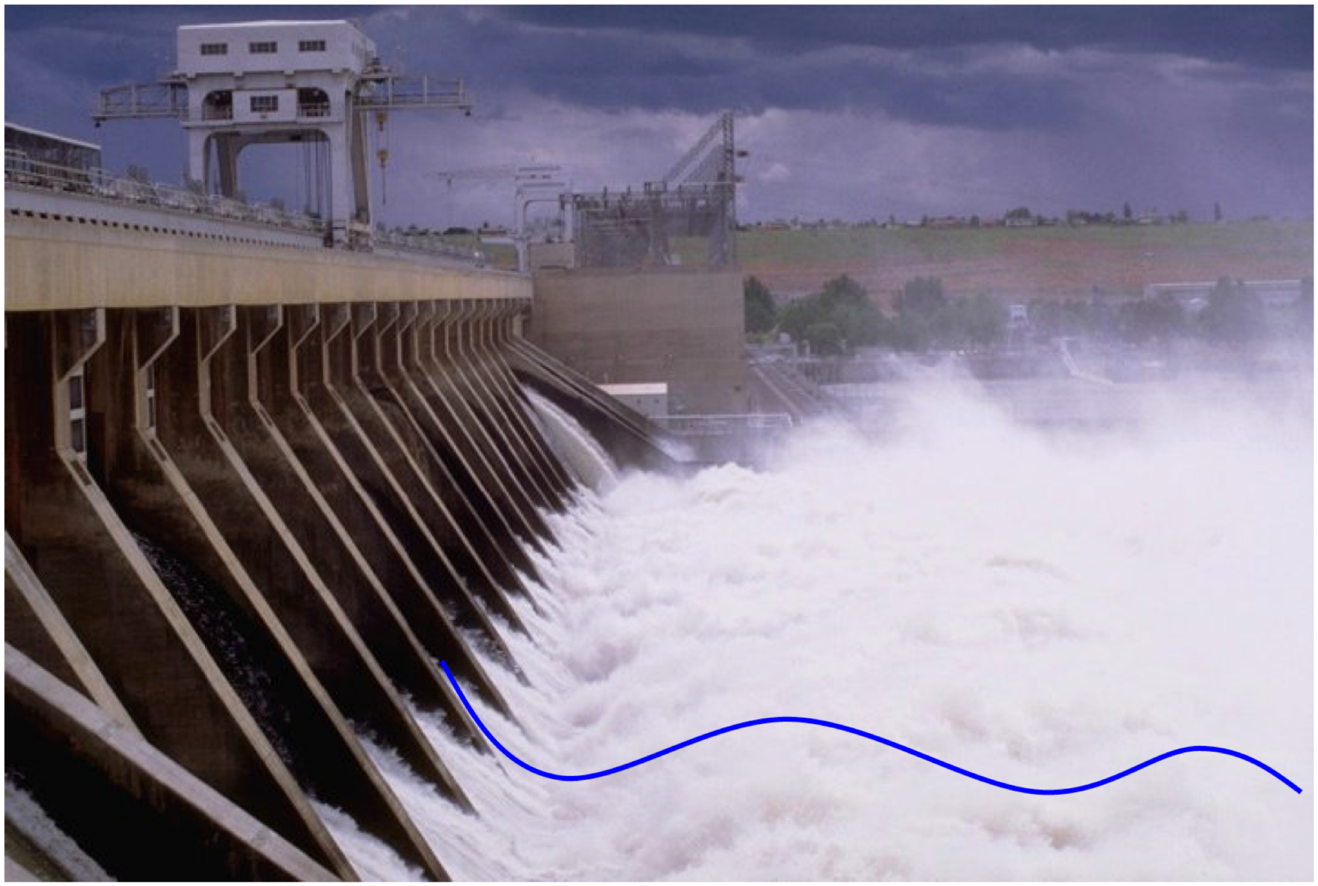
Map of relevant sites
LIGO
Test explosion site
and nearest previously
proposed turbine
20 km
Nearest
proposed
turbine
most distant State Line
measurement site (18 km)
most distant Nine Canyon
measurement site (10 km)
Nine Canyon: 49 x 1.3 MW and
14 x 2.3 MW, Siemens
State Line: 400 x
0.66 MW, Vesta
Geneva
Junction
Mathews
Corner
Eltopia
Sagemoor
Glade
West Richland
Richland
Benton City
West Pasco
Pasco
Kennewick
Badger
Finley
Prosser
Horse Heaven
Snake River
Le Grow
Page
Eureka
Ash
Windust
Scott
Walker
Sheffler
Lowden
Touchet
Port Kelley
Paterson
Plymouth
Umatilla
Berrian
Irrigon

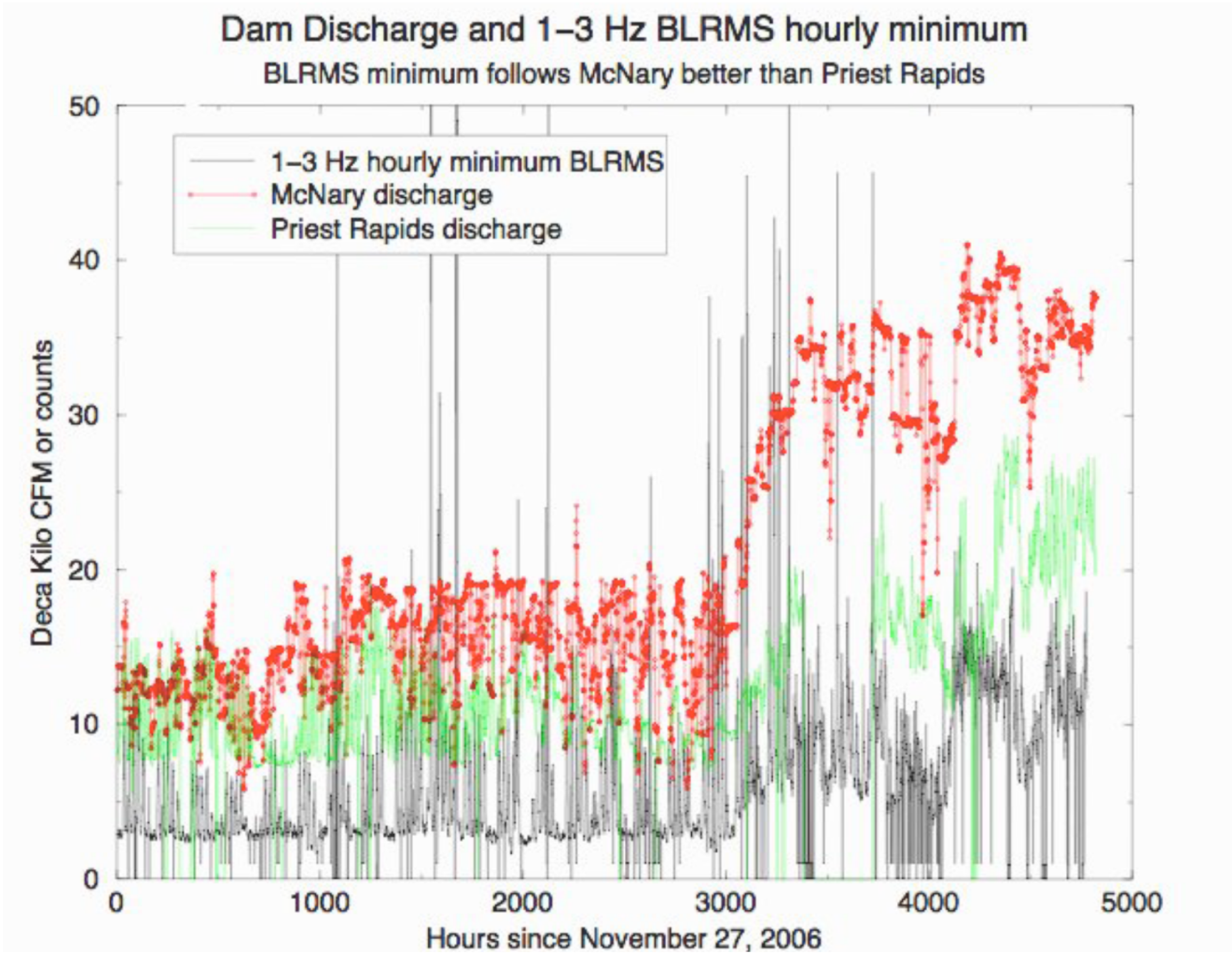


50 km
Firing Center Rd
31.12 mi
20.00 mi
Measure distance
Click on the map to add to your path
Total distance: 31.12 mi (50.08 km)
Ellensburg
Holmes
Cliffdell
Nile
Naches
Tieton
Rimrock
Selah
Yakima
Union Gap
Tampico
Wapato
Toppenish
White Swan
YAKAMA INDIAN RESERVATION
Satus
Grandview
Mabton
Beverly
Mattawa
Royal City
Smyrna
Marine View
Warden
Othello
Bruce
Hatton
Pierce
Pearl
Basin City
Mesa Edwards
Eltopia
Sagemoor
Glade
Connell
Kahlotus
Richland
Benton City
Kennewick
Finley
Page
Prescott
Waitsburg
Walla Walla
Touchet
Stateline
Milton-Freewater
Paterson
Irrigon
Boardman
Hermiston
Stanfield
Echo
Pendleton
UMATILLA RESERVATION
Athena
Bickleton
Dot
Pleasant Valley
Goldendale
Klickitat
Goodnoe Hills
Arlington
Bates
Rufus
Wasco
The Dalles
Firwood
Glenwood
Parrott Crossing
Adams
Providence
Lind
Paha
Ralston
Benge
Washtucna
Hooper
Ayer
Perry
Starbuck
Dixie
Kooskooskie
Hutterian Brethren
Layers
Imagery ©2024 TerraMetrics, Map data ©2024 Google
United States
Terms
Privacy
Send Product Feedback
10 mi


Firing Center Rd
60 km
0
20.00 mi
36.34 mi
Ellensburg
Holmes
Cliffdell
Nile
Naches
Tieton
Rimrock
Selah
Yakima
Union Gap
Tampico
Wapato
Toppenish
Granger
White Swan
Satus
YAKAMA INDIAN RESERVATION
Adams
Grandview
Mabton
Prosser
Benton City
Richland
Kennewick
Finley
Beverly
Mattawa
Desert Aire
Hanford Reach National Monument
Pierce
Pearl
Royal City
Smyrna
Marine View
Warden
Othello
Bruce
Hatton
Connell
Basin City
Mesa
Edwards
Eltopia
Sagemoor
Hutterian Brethren
Paha
Lind
Ralston
Providence
Benge
Washtucna
Hooper
Kahlotus
Ayer
Perry
Starbuck
Page
Prescott
Waitsburg
Dixie
Walla Walla
Touchet
Stateline
Kooskooskie
Milton-Freewater
Parrott Crossing
Glenwood
Firwood
Bickleton
Dot
Paterson
Irrigon
Boardman
Hermiston
Stanfield
Echo
Athena
Pendleton
UMATILLA RESERVATION
Klickitat
Goldendale
Pleasant Valley
Goodnoe Hills
Rufus
Bates
Arlington
The Dalles
Wasco
Layers
Measure distance
Click on the map to add to your path
Total distance: 36.34 mi (58.48 km)
Imagery ©2024 TerraMetrics, Map data ©2024 Google
United States
Terms
Privacy
Send Product Feedback
10 mi

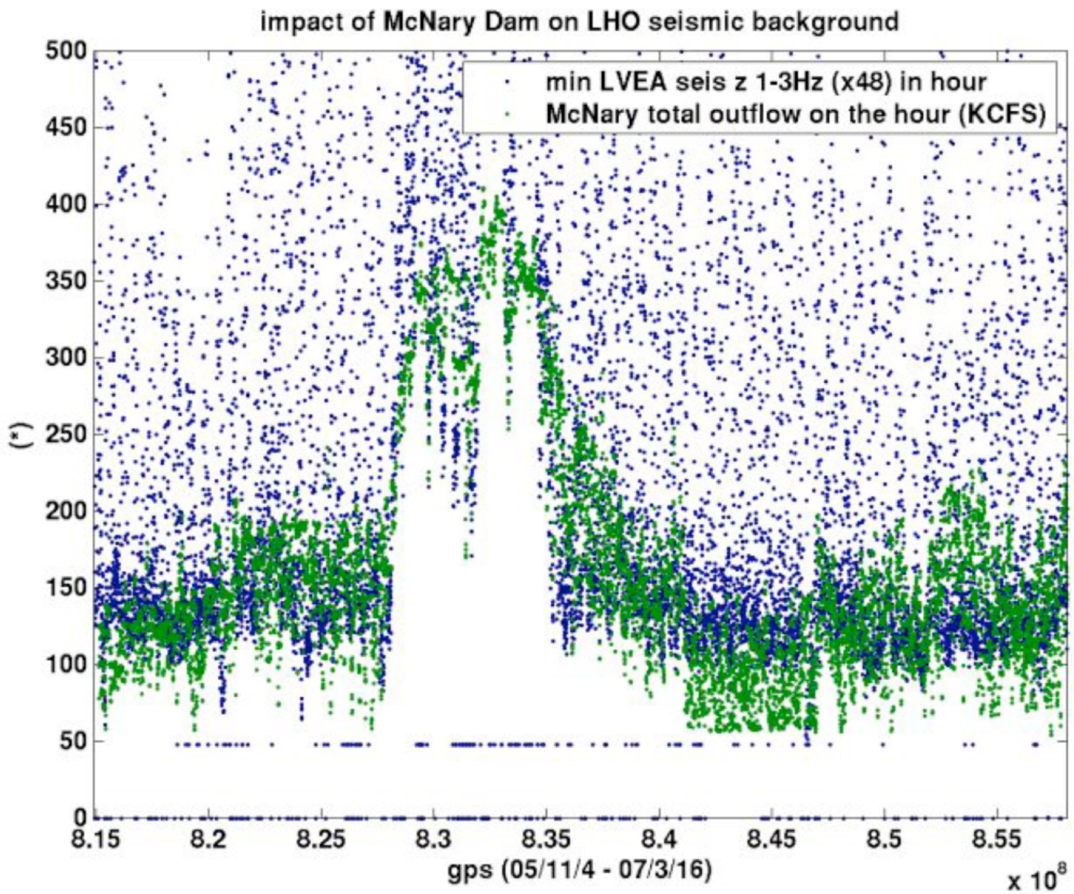
Dam affects inspiral range through upconversion of seismic signal at 1.2 Hz. "Bounce" of water timed at 1 to 0.3 second.



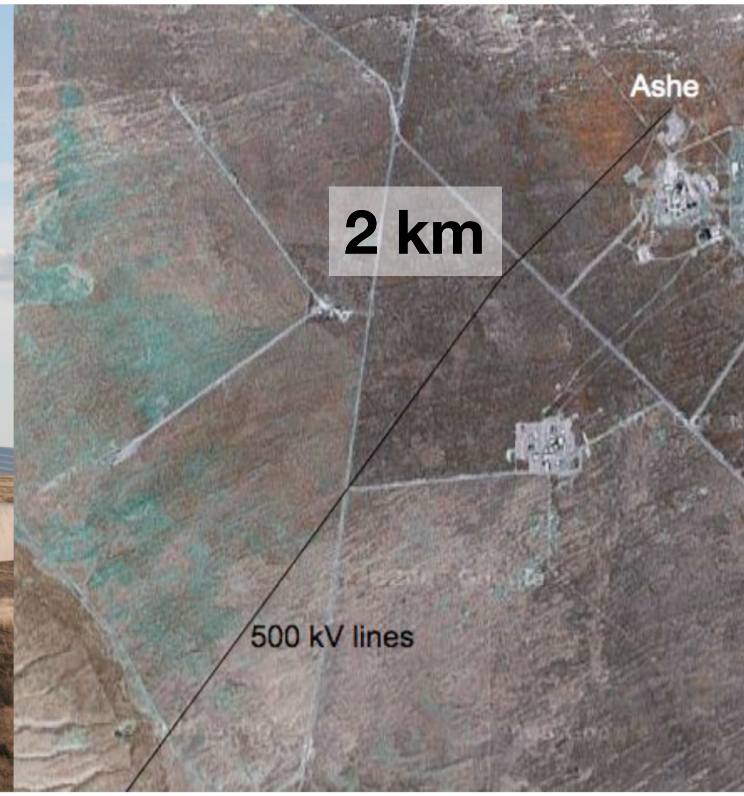


Dam Discharge and 1–3 Hz BLRMS hourly minimum
BLRMS minimum follows McNary better than Priest Rapids
1–3 Hz hourly minimum BLRMS
McNary discharge
Priest Rapids discharge
Deca Kilo CFM or counts
Hours since November 27, 2006
0
10
20
30
40
50
1000
2000
3000
4000
5000

Justins update showing entire run until present: dam has affected us for about 1/4 of the run so far



Transmission lines partly responsible for 60Hz peak in H1



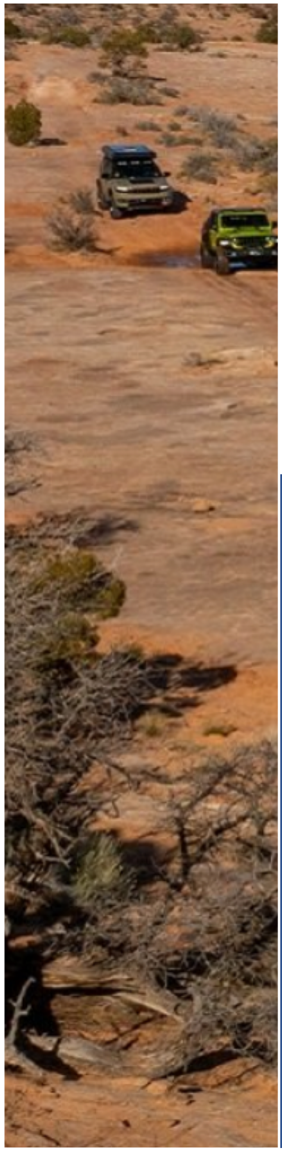
Study of 31 site-wide magnetometer events

magnetic event no.	GPS Time	LocalTime	voltage event?	DARM KW Event?	BPA event (resolution mostly 2s)	Q-scan LVEA_V2 peak f (Hz)	Predicted DARM 70 Hz from mag field	Actual DARM 70 Hz
1	817736343	Dec 04, 2005 04:58:49 PST	Yes		Capacitors in, Benton substation	497		
2	817824114	Dec 05, 2005 05:21:40 PST	Yes		Capacitors in, Benton substation	592	6.00E-08	2.00E-07
3	817911868	Dec 06, 2005 05:44:14 PST	Yes		Capacitors in, Benton substation	631		
4	818073843	Dec 08, 2005 02:43:50 PST	Yes	H1	Capacitors in, Ashe substation	352		
5	818159114	Dec 09, 2005 02:25:00 PST	Yes		Capacitors in, Benton substation	691		
6	818426006	Dec 12, 2005 04:33:12 PST	Yes	H2	Trip, Marion north bus when switching reactor	69		
7	818507471	Dec 13, 2005 03:10:58 PST	Yes		Capacitors in, Benton substation	592	6.00E-08	2.00E-07
8	818511507	Dec 13, 2005 04:18:13 PST	Yes		Capacitors in, Richland substation	417		
9	818515503	Dec 13, 2005 05:24:49 PST	Yes		Capacitors in, Ashe substation	417	6.00E-09	2.00E-07
10	818684261	Dec 15, 2005 04:17:28 PST	Yes		Capacitors in, Ashe substation	417		
11	819002198	Dec 18, 2005 20:36:24 PST	Yes		Capacitors in, Ashe substation	389		
12	819036727	Dec 19, 2005 06:11:54 PST	Yes	H2	Capacitors in, Richland substation	352		
13	819160196	Dec 20, 2005 16:29:42 PST	Yes		Capacitors in, Richland substation	337		
14	819211052	Dec 21, 2005 06:37:18 PST	Yes		Capacitors in, Richland substation	367		
15	819257186	Dec 21, 2005 19:26:12 PST	Yes	H1 And H2	Fault on Ashe-Slatt 500 kV line	68	3.00E-06	4.00E-06
16	819384812	Dec 23, 2005 06:53:18 PST	Yes	H1 And H2	Fault on Slatt-Buckley 500 kV line	95	6.00E-07	6.00E-07
17	819386152	Dec 23, 2005 07:15:39 PST	Yes	H1 And H2	Fault on Benton-Othello 115 kV line	53		
18	819673745	Dec 26, 2005 15:08:52 PST	Yes	H1 And H2	None found	95		
19	820394439	Jan 03, 2006 23:20:25 PST	Yes	H1 And H2	Trip, Ice Harbor-Franklin 115 kV line	68	5.00E-07	3.00E-07
20	820595204	Jan 06, 2006 07:06:31 PST	Yes	H2	Trip, Vantage-Schultz 500 kVline	50		
21	821270678	Jan 14, 2006 02:44:24 PST	Yes	H1 And H2	Trip, Benton-Franklin 230 kV line	53	1.40E-06	2.00E-06
22	821459495	Jan 16, 2006 07:11:22 PST	Yes	H1	Capacitors in, Richland substation	350		
23	823009424	Feb 03, 2006 05:43:31 PST	Yes	H1 And H2	Fault on Lower Monumental-Ashe 500 kV line	53		
24	823355073	Feb 07, 2006 05:44:19 PST	Yes	H1	Capacitors in, Benton substation	592		
25	825082556	Feb 27, 2006 05:35:42 PST	Yes		Capacitors in, Benton substation	691	2.00E-08	6.00E-07
26	825170442	Feb 28, 2006 06:00:28 PST	Yes		Capacitors in, Benton substation	497		
27	826119810	Mar 11, 2006 05:43:16 PST	Yes		Capacitors in, Benton substation	592		
28	827089513	Mar 22, 2006 11:04:59 PST	No		None found	mag at about 10	9.00E-08	2.00E-07
29	827506076	Mar 27, 2006 06:47:42 PST	Yes		Capacitors in, Benton substation	757	3.00E-08	2.00E-07
30	827592239	Mar 28, 2006 06:43:45 PST	Yes	H1	Capacitors in, Benton substation	592		
31	828112266	Apr 03, 2006 08:10:53 PST	No		None found	mag at about 10		

Collaboration with Mike Viles, BPA

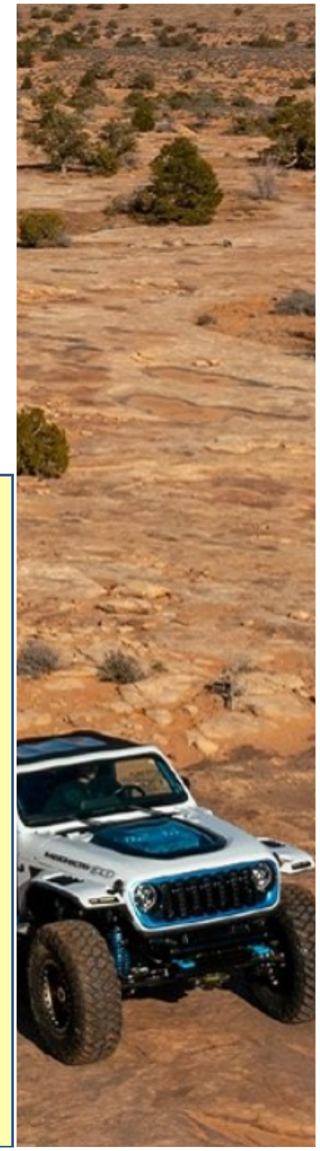
Suggested day-scale instrumented site evaluation

- Will not deal with earth tides, microseismic peak, wind driven seismicity that vary on week scales and greater
- Focus on local sources that are present daily but may not be captured by seismic maps and other external sources.
- Use imperfect but nimble setups so that we can measure at multiple sites, and alter our plans in order to investigate a signal.
- Focus on seismic and magnetic signals, which are the worst environmental noise for LIGO

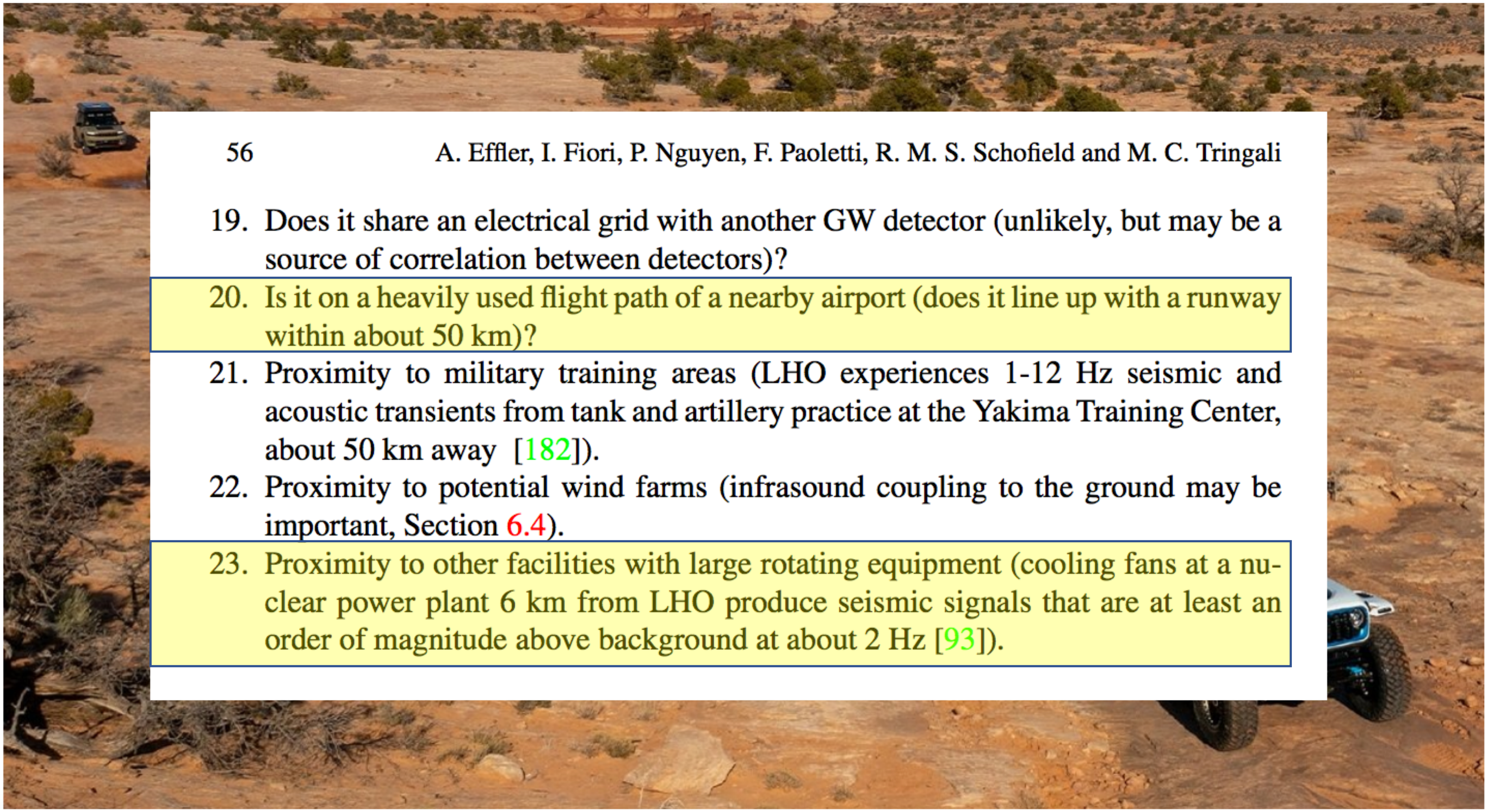


Prior to actual site measurements, candidate sites can be evaluated using information available on the internet and Google Earth. This includes most of the considerations in the list below:

1. Geology.
2. Microseismic peak level (minimize relative motion of detector stations, Section 6.3).
3. Wind speed distribution (minimize wind greater than about 10 m/s).
4. Expected weather changes associated with climate change.
5. Nearest train tracks and density of train traffic on those tracks (trains can produce 1-3 Hz seismic noise, especially within 20 km, and, if electric, can produce magnetic noise transients below 10 Hz especially less than 10 km away, Section 9.4).
6. Nearest highway, and truck traffic density (especially within 10 km; frequency, given by axle spacing and speed, is generally in the 4-15 Hz band; transient vibrations from trucks can be an order of magnitude worse than from cars, and at lower frequencies due to greater axle spacing [180]).
7. Nearest bridges and viaducts (including those for trains), which may have structural resonances that are excited by vehicles (see also Section 6.4).
8. Conditions of nearest roads (the largest 4-15 Hz seismic signal at a LIGO Hanford Observatory (LHO) end station was reduced by a factor of 2 to 3 when highway 240, 2 km away, was resurfaced [98]).
9. Nearest gravel or dirt road and traffic density (gravel and dirt roads typically produce much more vibration noise per vehicle than other roads).
10. Off-highway recreational vehicle activity within 10 km (the signal from variations in force against the ground is typically in the 3-15 Hz band).



11. Nearest activity involving heavy equipment, such as mining and quarrying (varying forces from massive vehicle motions can be more important than higher frequency activities such as rock crushing, because of greater attenuation of high frequencies).
12. Potential logging activities (also mainly due to variations in force from massive vehicles).
13. Nearest likely construction (again the worst sources tend to be massive earth moving equipment in motion, mainly within 20 km).
14. Nearest town (within 20 km).
15. Population density.
16. Nearest dam. LHO astrophysical range was limited at night during spring season high-water flow by 1-3 Hz vibration from water flow over McNary Dam, 60 km away) [91, 92].
17. Nearest power substation (mains current returning in the ground to a substation near the Ligo Livingston Observatory (LLO) travels on the grounded beamtube and produces magnetic glitches inside the buildings as stoves, heaters, etc. in Livingston turn on and off, Section 9.1).
18. Nearest trunk power line (some of the largest magnetic transients at LHO are produced by current fluctuations in a 500 kV, 700-3000 A transmission line about 2 km away [181]).



19. Does it share an electrical grid with another GW detector (unlikely, but may be a source of correlation between detectors)?
20. Is it on a heavily used flight path of a nearby airport (does it line up with a runway within about 50 km)?
21. Proximity to military training areas (LHO experiences 1-12 Hz seismic and acoustic transients from tank and artillery practice at the Yakima Training Center, about 50 km away [182]).
22. Proximity to potential wind farms (infrasound coupling to the ground may be important, Section 6.4).
23. Proximity to other facilities with large rotating equipment (cooling fans at a nuclear power plant 6 km from LHO produce seismic signals that are at least an order of magnitude above background at about 2 Hz [93]).

This workshop’s activities

- Identify truck transients from roads around the site
- Determine if the Ashe-Slatt, Ashe-Marion transmission lines are the main sources of magnetic fields and transients
- Try out a nimble system where we collect data and evaluate it “in the van”
- We will use a WebDAQ acquisition system that allows us to monitor spectra real-time
- We will use jupyter notebooks to display the data in different ways “in the van”